Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report 2021

Max Planck Institute for Astronomy

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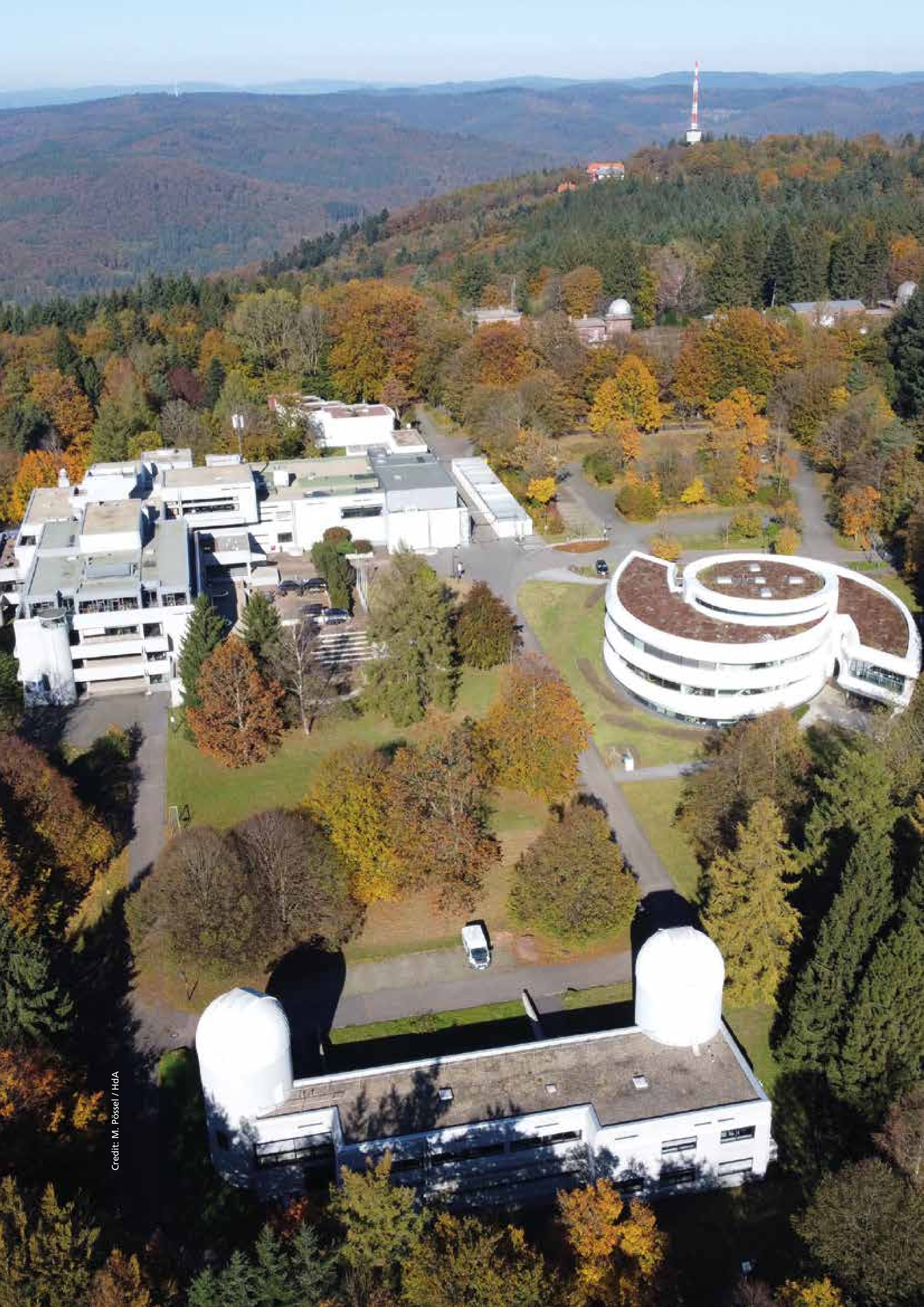


Credit: M. Pössel / HdA

Preface

The universe never ceases to amaze. It harbors an astonishing range of phenomena and conditions, reveals an immense amount of self-organization driven by the laws of physics, and hosts an unimagined variety of other worlds. Through thought, hard work and creativity, paired with innovative tools for observations, astronomers get to understand our universe better, year after year.

It is in this spirit that the Max Planck Institute for Astronomy pursues its research, with a particular focus on the formation of galaxies, stars, and planets and the analysis of the structure of exoplanets and their atmospheres. We develop and build instrumentation, we observe and model data, and we turn that information into insights through theory and numerical simulations. We perform experiments to understand key processes in the interstellar medium and planet-forming disks, especially the formation of complex organic molecules and the origins of life.

But like all research, our astronomical research is people-driven. So, at MPIA we are striving to build and foster an ambitious, enthusiastic and diverse community of excellent researchers, students and engineers. This report provides some snapshots of what we did and what we learned in 2021 about our universe.

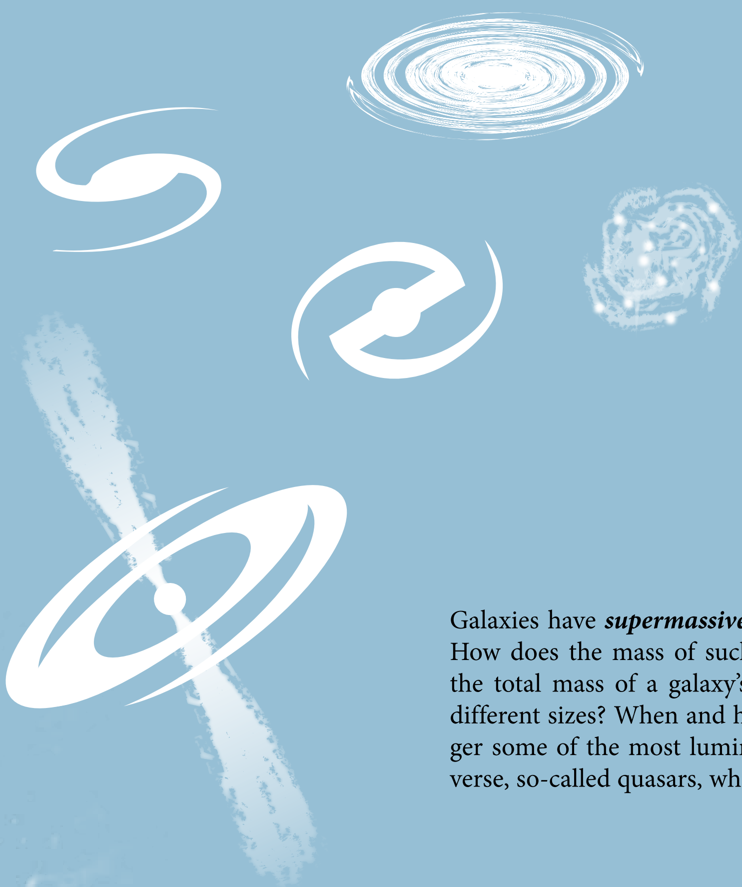
Thomas Henning, Laura Kreidberg, and Hans-Walter Rix

Heidelberg, December 2022

I. MPIA in a Nutshell

Credit: M. Pössel / HdA

Our Fields of Research: Galaxies and Cosmology

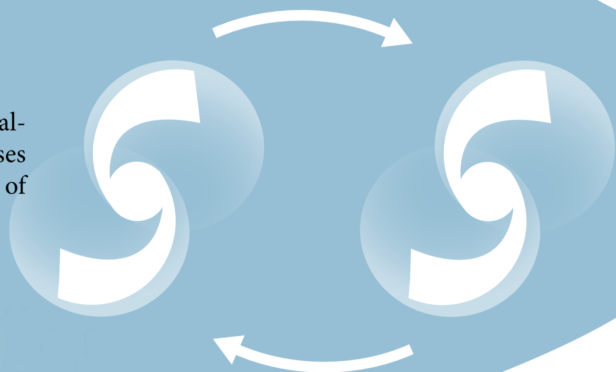


Galaxies come in many shapes and sizes. How do these differences arise? And what factors are responsible for how many stars a galaxy produces?

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

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

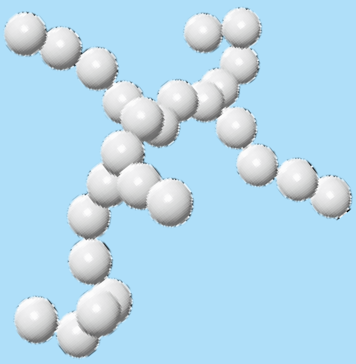
Galaxies grow as they merge with other galaxies or swallow smaller galaxies. How do these growth processes work in detail? How do they influence the properties of different types of galaxies?



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

Exoplanets and their properties, planet and star formation

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



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

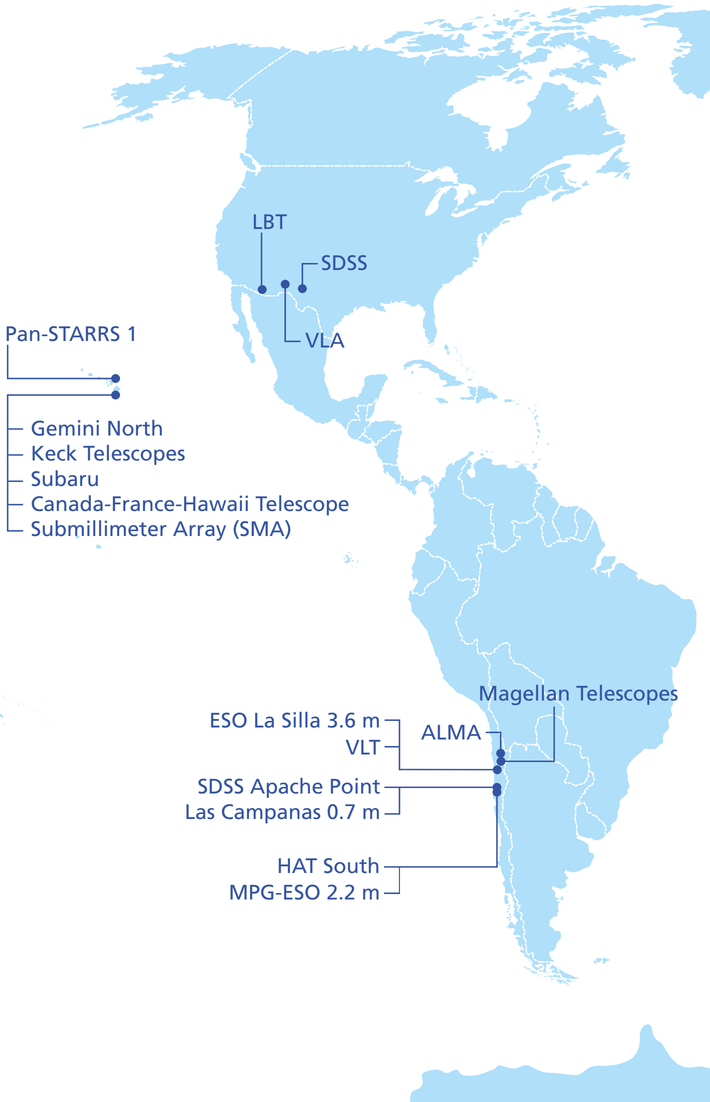
Since 1995, astronomers have discovered more than 4800 ***exoplanets*** (planets orbiting stars other than the Sun). What can these widely different planetary systems tell us about planet formation?

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

MPIA Telescopes all Over the World

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

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



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

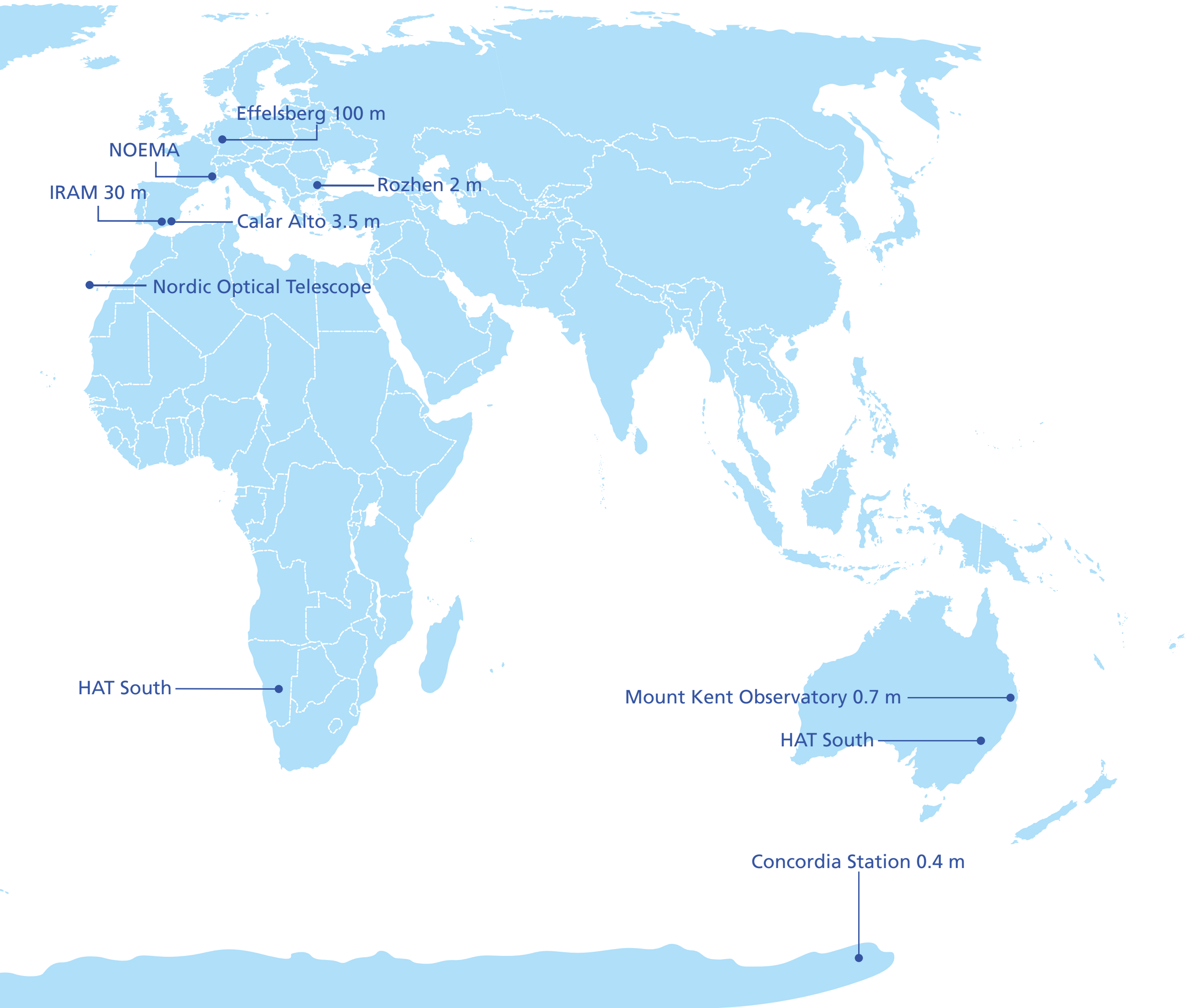
Credit: ESO

The Subaru telescope, operated by Japan's National Observatory NAOJ, is located on Mauna Kea on Hawai'i.

Credit: NAOJ

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

Credit: NASA / J. Ross



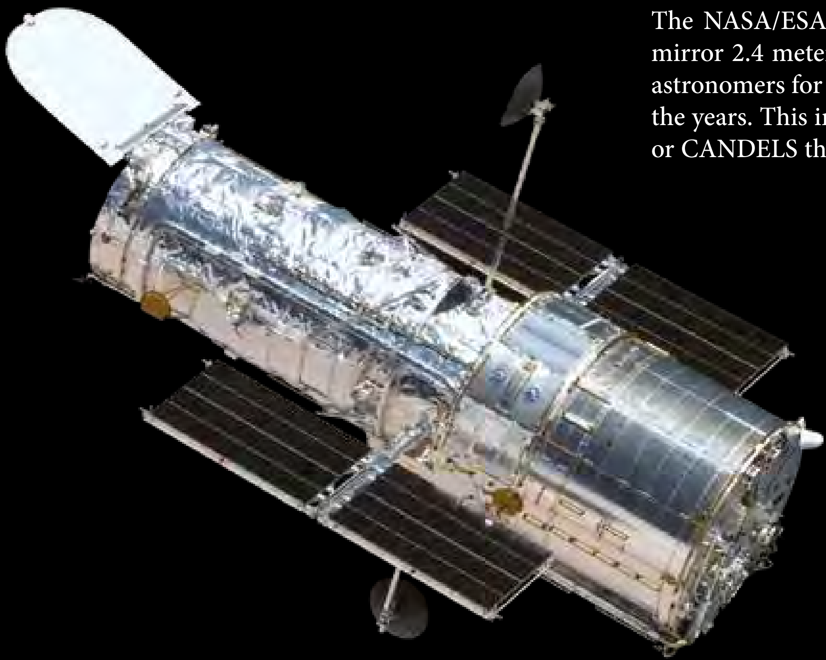
The Nordic Optical Telescope (NOT) on La Palma is a 2.56 m mirror telescope. MPIA is involved in constructing the instrument NTE, the "NOT Transient Explorer".

Credit: B. Tubbs

The Submillimetre 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.

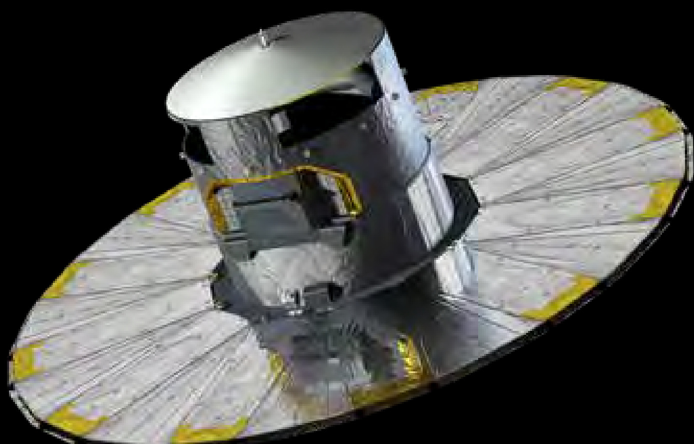
Credit: J. Weintroub

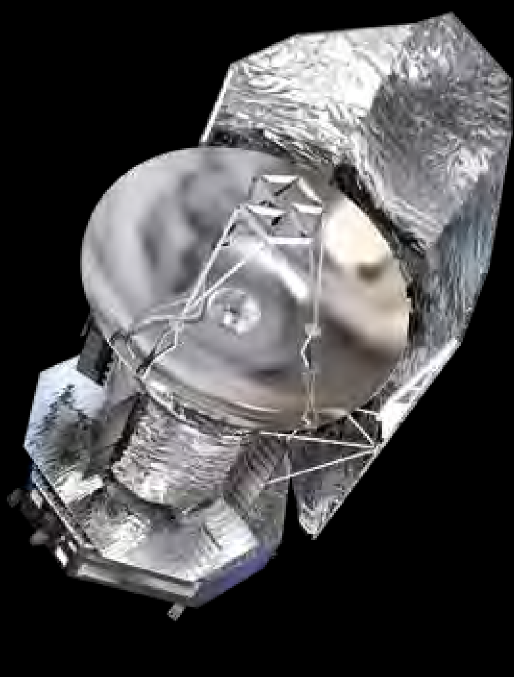
Space Telescopes



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

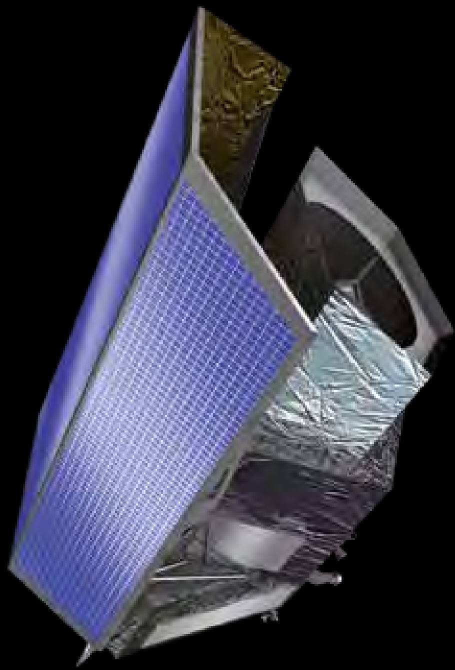
ESA's astrometry satellite Gaia is measuring the distance from Earth to more than a billion stars with unprecedented precision. The MPIA Gaia group leads the effort of using this data to reconstruct the astrophysical properties of those stars, played a key role in the data releases DR2 (April 2018),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





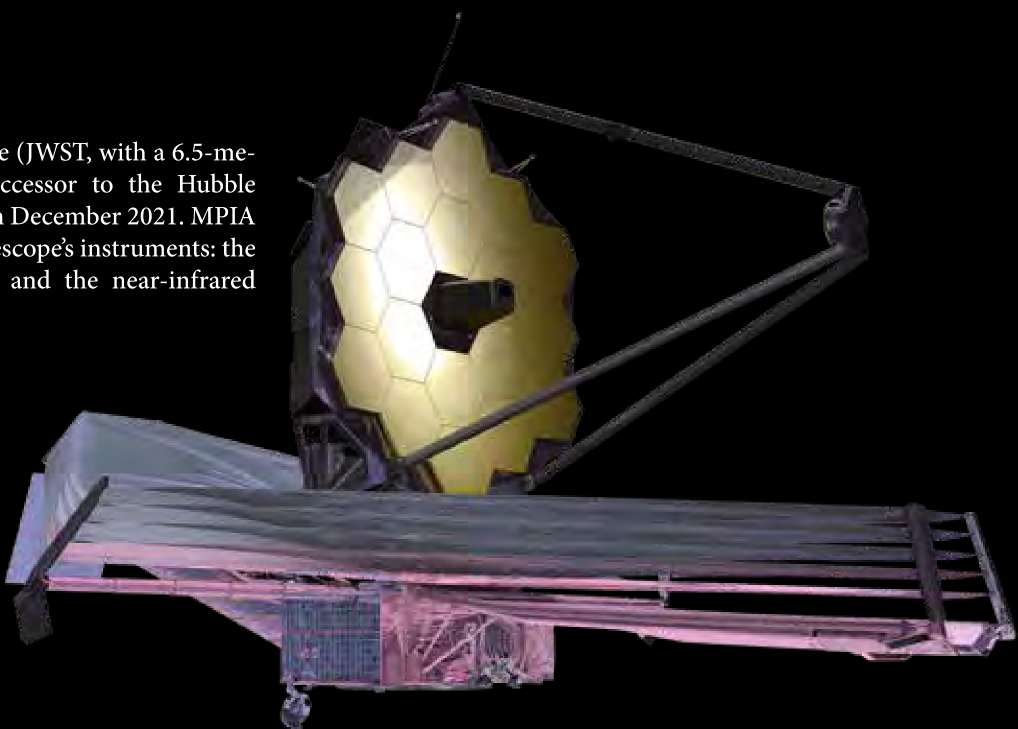
MPIA contributed to the construction of ESA's infrared observatory Herschel: We developed key components for the PACS instrument aboard the Herschel satellite, and were responsible for a number of observational programs undertaken with Herschel.

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



The Nancy Grace Roman Space Telescope is an optical to near-infrared 2.4-meter space telescope with an anticipated launch in 2026. Its objectives include the search and study of extrasolar planets and probing the expansion history of the Universe and the growth of cosmic structure, intending to measure the effects of dark energy. MPIA develops the precision mechanisms for the optical elements of the CGI instrument, an ultra-high contrast coronagraphic camera, and 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.

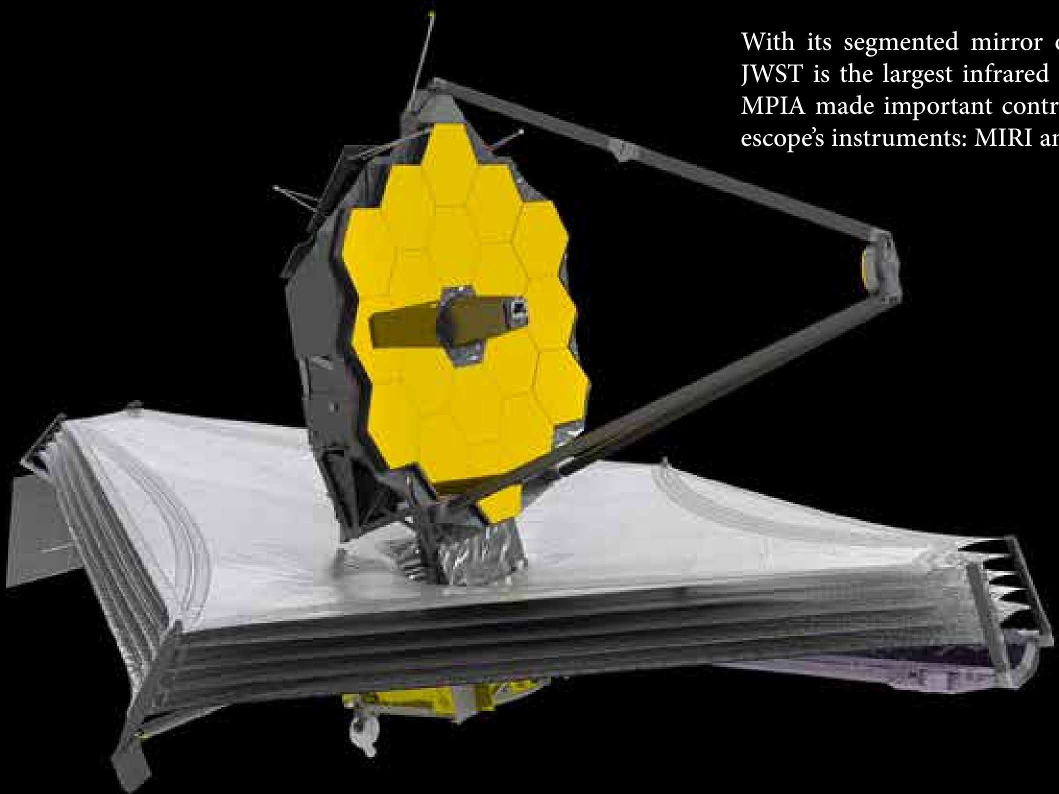


Credits: NASA, ESA

James Webb Space Telescope

Credit: Arianespace, ESA, NASA, CSA, CNES

The James Webb Space Telescope (JWST) successfully launched on 25 December 2021. After arriving in an orbit around Earth, it began its journey to a destination 1.5 million kilometers away from home. MPIA has participated in the commissioning of JWST's instruments.



With its segmented mirror of 6.5 meters in diameter JWST is the largest infrared space telescope ever built. MPIA made important contributions to two of the telescope's instruments: MIRI and NIRSpec.

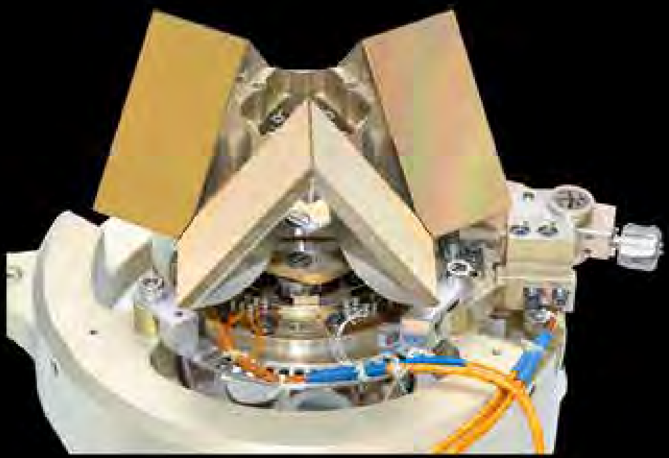
Credit: ESA / ATG medialab

The JWST launched from Kourou in French Guiana, Europe's spaceport in South America, on an Ariane 5 rocket. JWST had to be folded like an intricate origami to fit inside the rocket's fairing. It deployed as planned within the first two weeks after launch.

Credit: ESA / D. Ducros

The filter wheel mechanism makes MIRI a powerful scientific instrument. Except for the optical elements, the MPIA has planned, designed, built and tested the filter wheel mechanism. The 18 optical elements include filters to narrow the wavelength range, coronagraphs to cover bright objects, and a prism.

Credit: MPIA

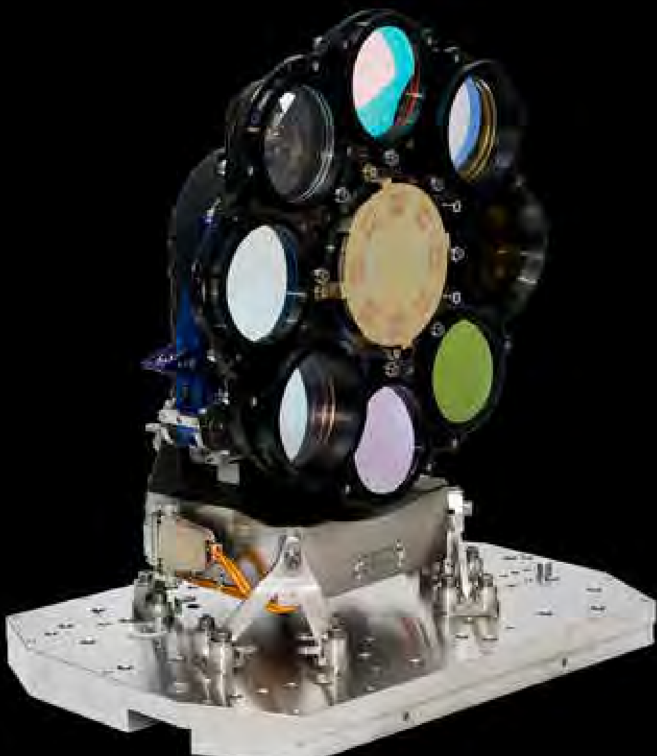


MPIA contributed two mechanisms for the MIRI spectrograph. Their reflective gratings and dichroic filters permit selecting different spectral ranges between 5 and 28 µm with varying resolutions. MPIA also led the development of MIRI's electrical system.

Credit: Hensoldt AG

With the support of European partners, MPIA has been responsible for the electrical system of the NIRSpec mechanisms such as the filter wheel. NIRSpec was constructed by an industrial consortium led byAstrium/ EADS, now Airbus.

Credit: Hensoldt AG



Major conferences

Extragalactic jets on all scales – launching, propagation, termination
MPIA Summer Conference
14 – 18 June
Online conference

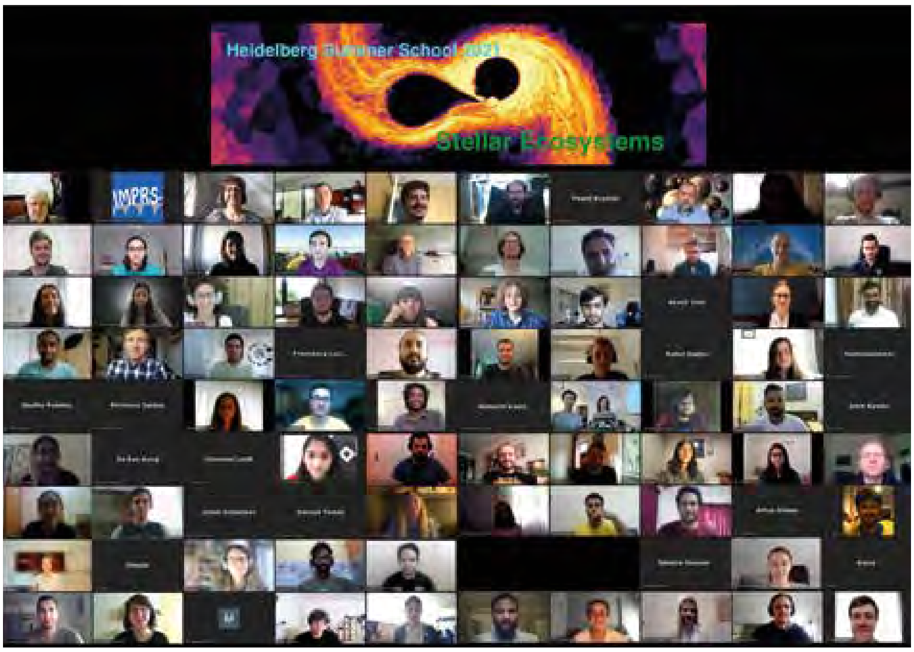
Ringberg Meeting: Puzzles of Star Formation
11 – 14 July
Ringberg Castle, Tegernsee

Stellar Ecosystems
Heidelberg Summer School
13 – 17 September
Online conference

Credit: H. Beuther / MPIA

Fig. I.2: Participants of the Ringberg Meeting "Puzzles of Star Formation".

Fig. I.1: Participants of the (virtual) summer school on Stellar Ecosystems.



Credit: C. Fendt / MPIA

Major Grants and Awards

Credit: L. Kreidberg / MPIA

Laura Kreidberg

Credit: K. Gös

Miriam Keppler

Credit: A. Gehrig

Michelle Ziegler

Laura Kreidberg
was awarded the Annie Jump Cannon Award of the American Astronomical Society

Miriam Keppler
received the A&A Best PhD Thesis Award

Olaf Fischer
was awarded the Hanno and Ruth Roelin Prize for Science Outreach

Michelle Ziegler
was honored by the Rhine-Neckar Chamber of Industry and Commerce (IHK) with the Willhelm Müller Foundation's sponsorship award for the best apprentice of the class of 2020

The Max Planck Institute for Astronomy
received a certificate from the Rhine-Neckar Chamber of Industry and Commerce in recognition of its excellent performance as a training company

Trifon Trifonov
was awarded the VIHREN science grant from the Bulgarian National Science Fund (worth 525 000 Euros over the next five years)

Patzer Prizes 2020

Felix Bosco, MPIA
for his publication "Spatially Resolving the Kinematics of the < = 100 μas Quasar Broad-line Region Using Spectroastrometry II. The First Tentative Detection in a Luminous Quasar at $z = 2.3$" (2021, ApJ, 919, 31)

Maria-Claudia Ramirez-Tannus, MPIA
for her publication "A relation between the radial velocity dispersion of young clusters and their age: Evidence for hardening as the formation scenario of massive close binaries" (2021, A&A, 645, L10)

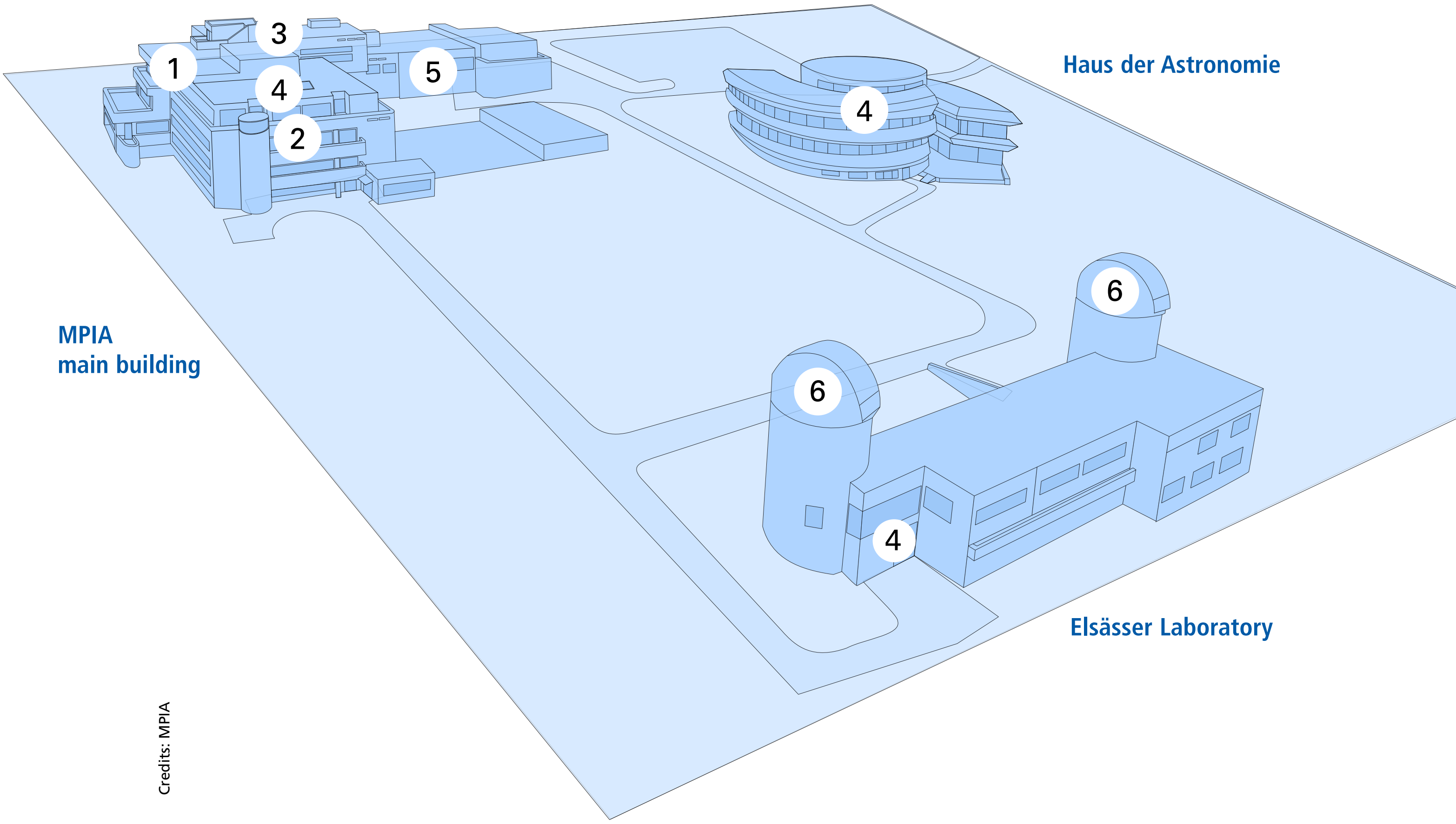
Oliver Völkel, MPIA
for his publication "Linking planetary embryo formation to planetesimal formation: II. The effect of pebble accretion in the terrestrial planet zone" (2021, A&A, 645, 132)

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.

50 cm and 70 cm telescopes for testing and training purposes, here the 50 cm HdA / MPIA telescope.

People at MPIA

392

employees
keep the institute running
190 of these are scientists
including 95 junior scientists
or long-term visitors
and 52 PhD students

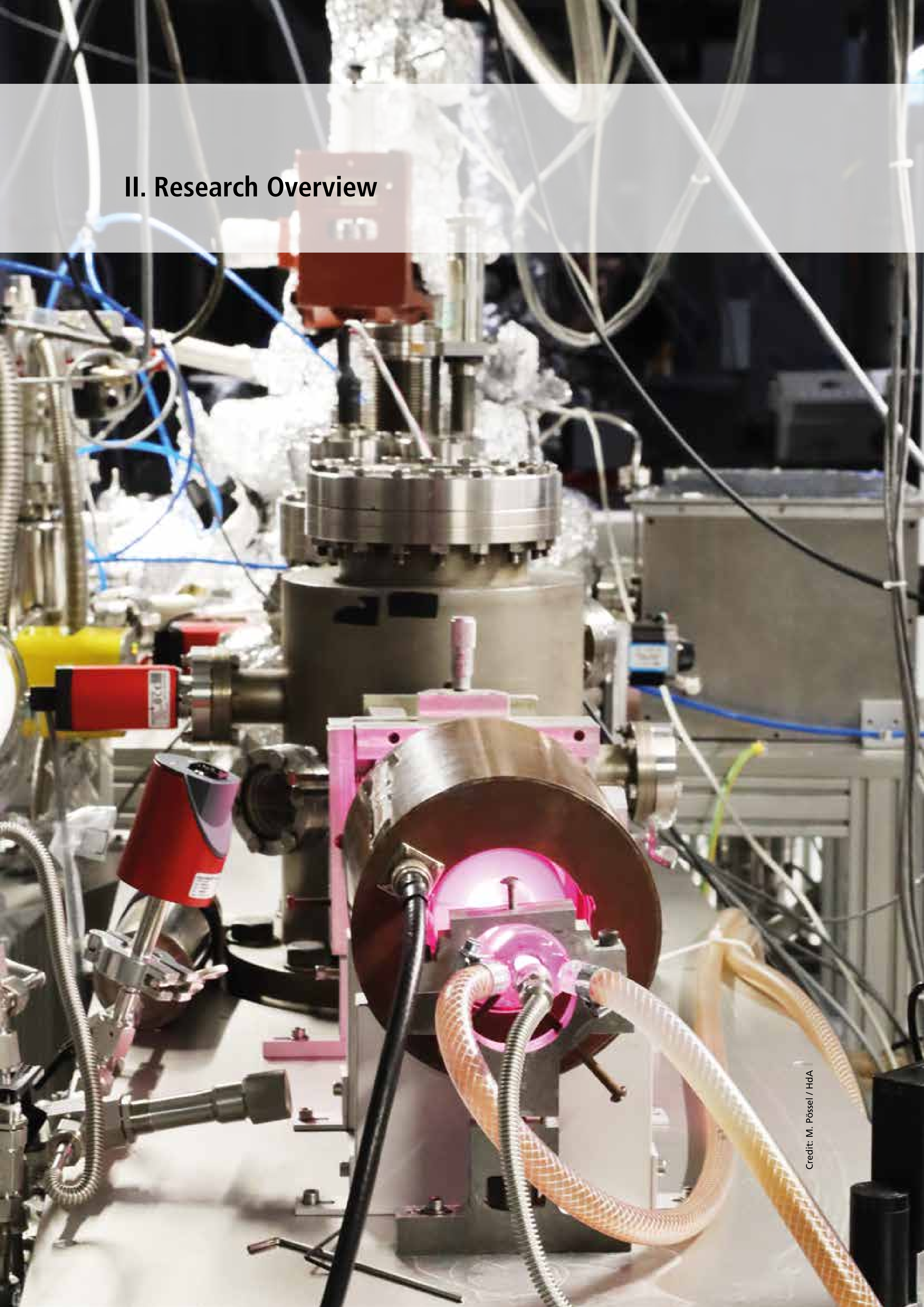
9

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

Fig. I.3: The MPIA campus in October 2021.

Credit: D. Elsässer

II. Research Overview



Credit: M. Pössel / HdA

II.1 Research Overview

Planet and Star Formation (PSF)

Director: Prof. Dr. Thomas K. Henning

The origin of stars and their planets

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

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

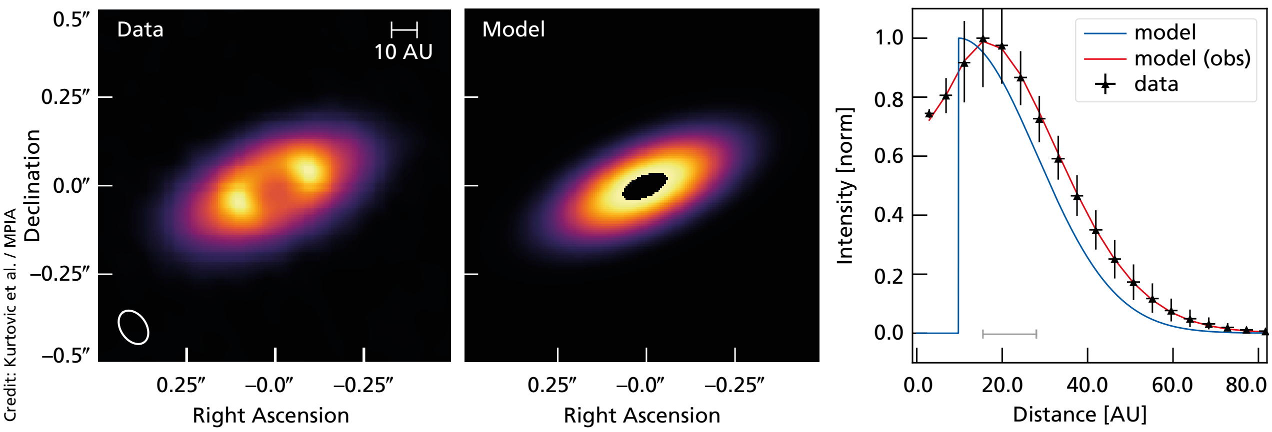
Scientists in the PSF department investigate a broad range of open questions related to the process of star and planet formation, combining multi-wavelength observations with large-scale numerical simulations and specially designed laboratory experiments.

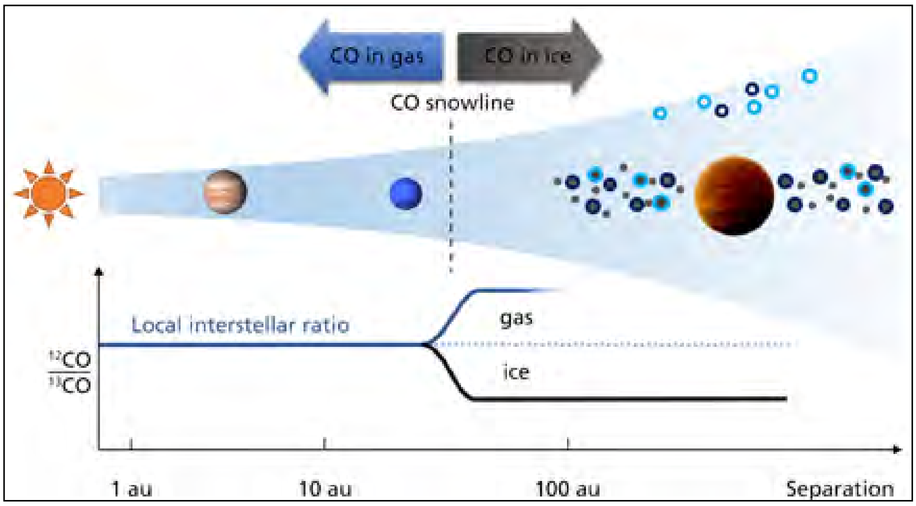
Observing the formation of stars and planets first-hand

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

PSF researchers use a comprehensive set of telescopes and facilities for their work, including the Hubble Space Telescope and ground-based facilities such as ESO's Very Large Telescope, the Large Binocular Telescope in Arizona, the NOrthern Extended Millimeter Array (NOEMA), the Atacama Large Millimeter/ Submillimeter Array (ALMA), and the Karl G. Jansky Very Large Array. Scientists in this department are moreover actively involved in laying the foundations for the science projects that will be possible with the James Webb Space Telescope, which was launched in 2021, and will return first science data in summer 2022. PSF scientists together with MPIA engineers are leading the development and

Fig. II.1.1: Astronomers led by Nicolas Kurtovic from the PSF department detected ring-like structures in the protoplanetary disks of young very low-mass stars, which are considerably smaller and less massive than previously known such disks. The figure shows observational data and a model of the dust disk around the VLMS MHO6. Left: Image of the dust disk. Middle: The disk model with a 20 au wide central hole, which is consistent with a Saturn-mass planet located at a distance of 7 au from the star, accreting disk material. Right: Radial profile of the model (blue) and after convolving it with the telescope's angular resolution (red). The black symbols represent the data obtained from the measured brightness distribution. The gray bar corresponds to the angular resolution of the observations.





Credit: Y. Zhang / Leiden Observatory, MPIA graphics department

Fig. II.1.2: Illustration of the birth environments of planets in a proto-planetary disk that formed around a young star. The two planets inside the CO snowline denote Jupiter and Neptune at their current locations. The planet TYC 8998 b, which was examined by a group of astronomers that includes MPIA's Paul Mollière, formed far outside this regime. At such a distance from the parent star, most carbon is expected to have been locked up in CO-ice and built the planet's main carbon reservoir. Consequently, the ice was rich in carbon-13 resulting in the observed isotope ratio in the planet's atmosphere.The astronomers managed to observe tell-tale spectral traces of this carbon-13, marking the first time it has been possible to distinguish different isotopes of an element in an exoplanet atmosphere.

production of all mechanisms for the coronagraph of the Roman Space Telescope. With a large contribution to the mid-infrared instrument METIS, PSF scientists are contributing to the instrumentation program for ESO's Extremely Large Telescope, which should commence science operations in 2028. Observations with these telescopes provide insights into the physics and chemistry of the interstellar medium and the earliest stages of star and planet formation, and allow MPIA scientists to discover and characterize exoplanets.

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

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

Understanding the origin of stars

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

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

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

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

A peek behind the curtain

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

Due to the basic laws of fluid dynamics – namely the conservation of angular momentum – the accretion of matter onto the central protostar happens predominantly via a circumstellar disk. Disks around the low-mass T Tauri stars and the intermediate-mass Herbig Ae/Be-stars are natural birthplaces for planetary systems. While the pre-main sequence star still accretes matter from the surrounding disk, some of the matter is ejected perpendicular to the disk in the form of molecular outflows, or as collimated, ionized, high-velocity jets. Direct observations of such disks and the associated accretion and outflow phenomena provide insights into both the formation of our own Solar System and the diversity of planetary systems in general. Rings, spirals, and enormously large inner holes in planet-forming disks all point to a vigorous planet formation process. As a matter of fact, scientists of the PSF Department were the first to discover a young giant planet embedded in such a disk. In addition, we could demonstrate the impact of the exoplanet on its birth environment and discovered a circumplanetary disk with ALMA observations.

Observing from the ground and from space

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

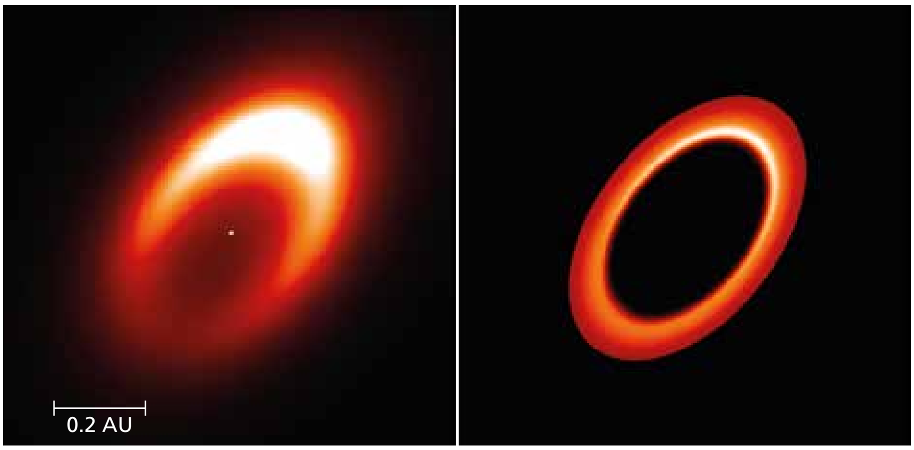
Presently, a strong focus of the department's work is on preparing projects in the field of star formation, protoplanetary disks, and exoplanets for the James Webb Space Telescope (JWST), the designated successor of the Hubble Space Telescope. The JWST was launched in December 2021. As a member of the consortium for the JWST mid-infrared instrument MIRI, we will have access to guaranteed time for this instrument.

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

Planet formation and the search for exoplanets

The detection of the first extrasolar planet around a Sun-like star in 1995 initiated a new era in the study of planet formation and the search and characterization of extra-

Fig. II.1.3: Producing ever more detailed data on protoplanetary disks is a major focus of the PSF department. This year, the MATISSE instrument at ESO's Very Large Telescope Interferometer, which the PSF department helped construct, uncovered evidence for a vortex at the inner rim of a planet-forming disk around a young star. The vortex appears to move on an orbit around its star similar to Mercury's orbit around the Sun. Astronomers think such vortices are sites where small particles converge and grow to form planets' building blocks. The figure shows the reconstructed image of the dusty disk (left) around the young star HD 163296, derived from the MATISSE observations. The false-colour image shows the thermal radiation from the disk at infrared wavelengths. The observations revealed a strong asymmetry which presents itself as a bright clump located at the upper right part in the image. A vortex concentrating material in a horseshoe-shaped region in the inner disk (as in the simulation shown on the right) could be causing this asymmetry.



Credit: J. Varga / Leiden Observatory, H. Meheut / CNRS / Lagrange solar planets. Suddenly, instead of a single example of a planetary system – our own Solar System – astronomers were able to examine, compare and contrast thousands of such systems.

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

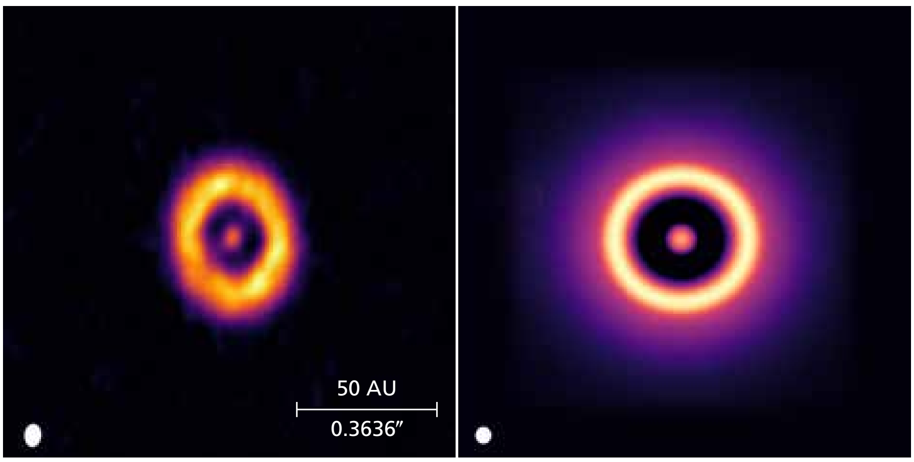
The CARMENES spectrograph at the Calar Alto Observatory is one of the most versatile instruments to search for exoplanets around M-type stars. A multi-year survey to unravel the statistics of low-mass planets around these red stars is near completion and has already returned a flood of exciting planet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

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

Star and planet formation in a computer

A comprehensive understanding of planet and star formation can only be reached when astronomical observations make a connection with fundamental physical processes. The theory program of the PSF department focuses on large-scale numerical simulations of protoplanetary disks, including the interplay between radiation, dynamics, chemistry and the evolution of dust grains, in order to link observations with an in-depth understanding of the physical and chemical processes

Fig. II.1.4: Understanding the underlying physical processes is key to the accurate modeling of planet formation. Work from the group of Paola Pinilla constitutes substantial progress in understanding most of the properties observed in dispersing planet-forming disks around newborn stars. The key ingredients of this new physical scenario are X-ray emissions from the central star and a calm inner disk, well shielded from the incident radiation. The scenario's predictive power has been tested by comparisons between observed and simulated dust distributions in transition disks, as in this figure: To the left, an image of the disk around the object CIDA1 at a wavelength of 0.9 mm obtained with the ALMA interferometer. The disk is slightly tilted with respect to the image plane. The right-hand part is a synthetic image of the dust distribution from the simulations performed by MPIA's Matías Gárate and collaborators.



Credit: Pinilla et al., Gárate et al. / MPIA during star and planet formation. The theory group of the PSF department is developing multi-dimensional radiative transfer codes which simulate the way radiation travels through molecular clouds and their cores, protoplanetary disks and the atmospheres of planets. These codes can be used for interpreting cloud and disk images and spectra, and they also allow researchers to employ magneto-hydrodynamic simulations and reconstruct how the object in question would look to observers. Simulations now allow us to connect the conditions in planet-forming disks with the observed properties of planet populations. Another important application is models of planetary atmospheres, where these codes allow for calculating transmission and emission spectra as they would be measured by telescopes on the ground or in space. High-resolution spectroscopy with CARMENES and measurements with the LBT have been used to characterize planetary atmospheres.

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

Linking the cosmos and the laboratory

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

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

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

The Origins of Life Laboratory

The premises for the Origins of Life Laboratory of the PSF Department were built in 2020, and the lab began operating its first experiment in 2021. It is devoted to studying chemistry in interstellar ice, particularly the formation of molecules that are related to the origin of life. So far, more than 270 molecular species have been identified in interstellar space, among which many are considered complex organic molecules and could have been the building blocks of life on early Earth.

The ice mantle on interstellar dust grains is the most important place where complex molecules are produced. Under extremely low temperatures and low-pressure conditions in interstellar clouds, gas phase atoms and molecules condense on the grain surface and form new chemical bonds. In the Origins lab we simulate the condition that is typical in molecular clouds, and experimentally study various physical and chemical processes on the surface of interstellar dust grain analogs.

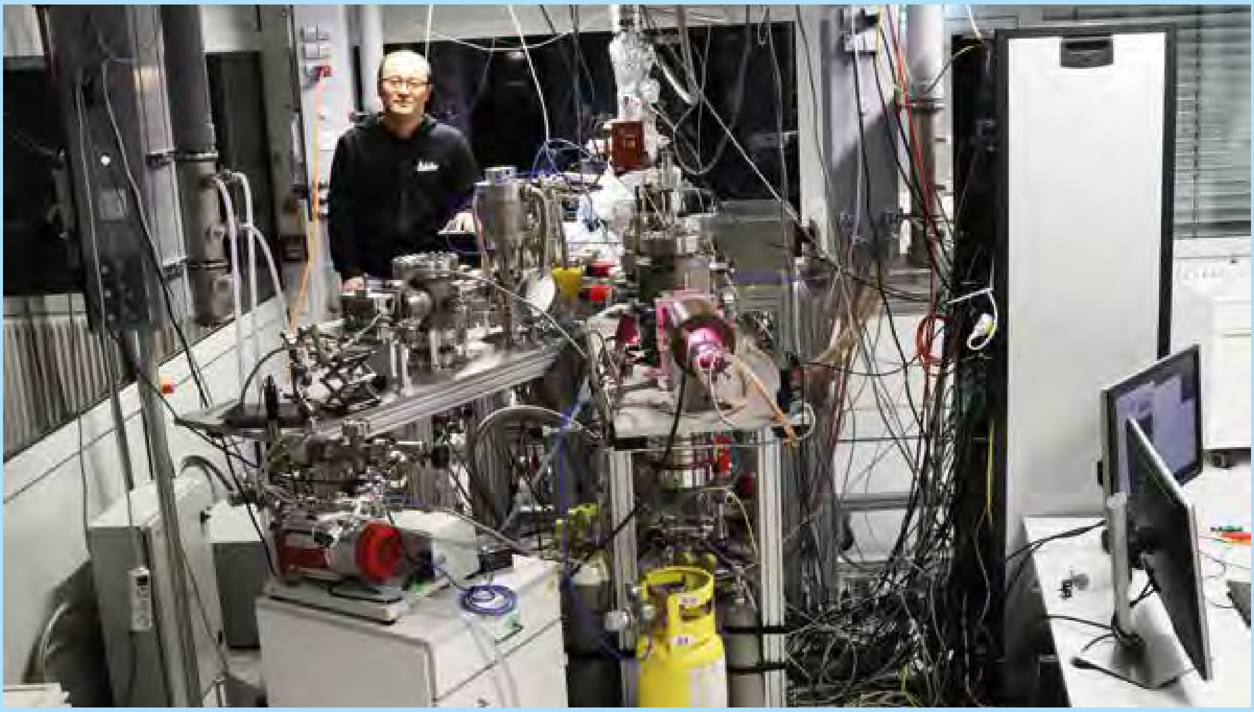
There are currently two experimental setups in the lab. The first one (pictured below) focuses on relatively simple molecules. Two highly collimated atomic/molecular beamlines are used to deposit reactants into the main reaction chamber. After condensation onto a cold substrate, atoms/molecules diffuse, react and form new molecules, which are then analyzed by an infrared spectrometer and quadrupole mass spectrometer.

This setup is also used to study some fundamental grain surface parameters, such as the desorption, diffusion, and sticking of various atoms and molecules on the surface. Once an ice mantle is already formed on the grain surface, further chemistry in the ice is dominated by irradiations of UV light or cosmic rays.

In order to study the chemistry induced by irradiations, the Origins lab is building another experimental setup. It uses UV light or keV electrons to trigger the chemistry in ice mixtures, and the composition of the ice can be monitored by an infrared spectrometer. What makes this setup powerful is the utilization of laser desorption ionization and Orbitrap mass spectrometry to identify larger organic molecules. Molecules in the ice are desorbed by a pulsed infrared laser, ionized by a UV laser, and subsequently analyzed by a very high mass resolution and high sensitivity Orbitrap mass spectrometer.

This technique is particularly powerful for the identification of trace amounts of prebiotic molecules such as amino acids, sugar, and nucleobases. This setup is currently under construction, and is expected to be ready in 2023.

Fig. II.1.5: Jiao He with the first working experiment in the newly opened Origins of Life laboratory.



Credit: M. Pössel / MPIA

II.2 Research Overview

Galaxies and Cosmology (GC)

Director: Prof. Dr. Hans-Walter Rix

How the Universe became interesting

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

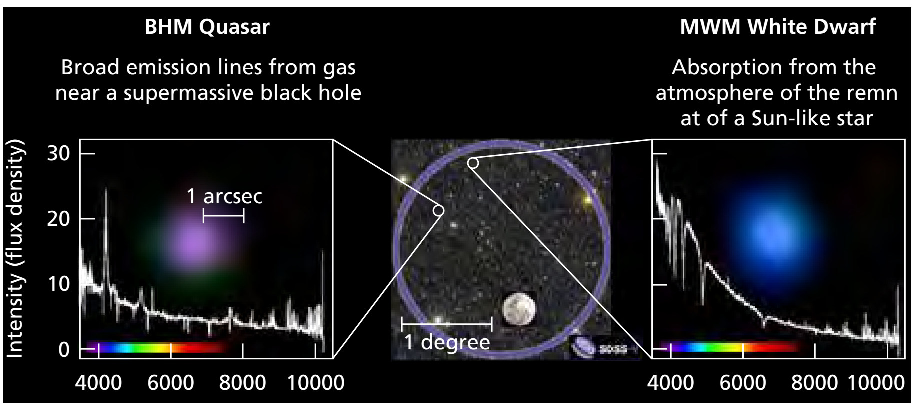
To understand quantitatively how such structure arose in an expanding Universe, however, current models need an unusual extra ingredient: dark matter, which possesses mass, and hence gravitational attraction, but does not interact at all with electromagnetic radiation. The specific nature of this dark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

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

Emerging order in the realm of galaxies

Galaxies exist over a vast range of physical scales: they vary by many orders of magnitude in their stellar masses, in their rate of producing new stars, the mass

Fig. II.2.1: Comprehensive surveys like the Sloan Digital Sky Survey (SDSS), where the GC department is currently co-leading the current survey incarnation (SDSS V), focussed on time-domain astrophysics, the Milky Way and its stars, as well as the growth of black holes. The figure shows first observational results from SDSS V: The central sky image is a single field of SDSS-V observations. The purple circle indicates the telescope’s field-of-view on the sky, with the full Moon shown as a size comparison. SDSS-V simultaneously observes 500 targets at a time within a circle of this size. The left panel shows the optical-light spectrum of a quasar – a supermassive black hole at the center of a distant galaxy, which is surrounded by a disk of hot, glowing gas. The right panel shows the image and spectrum of a white dwarf – the left-behind core of a low-mass star (like the Sun) after the end of its life.



Credit: H. Ibarra Medel, J. Trump, Y. Shen, G. Zasowski, and the SDSS-V Collaboration. Central *background image:* unWISE / NASA/JPL-Caltech / D. Lang (Perimeter Institute) of the black holes at their very centers, and their sheer physical size. Yet, as Edwin Hubble realized 80 years ago, these "island universes" are not as varied in their appearance and structure as the laws of physics would allow. Observations, particularly those made over the last 15 years, have confirmed this in ever greater detail: only a small fraction of the possible combinations of galaxies' characteristic quantities (stellar masses and ages, size, shape and central black hole mass) are actually realized in the Universe. Virtually all these physical properties are strongly correlated. In other words, the "realm of galaxies", to use Hubble's expression, exhibits a high degree of order. How did this order develop from the initial random mass fluctuations? That is the fundamental question of galaxy formation and a central issue in cosmology.

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

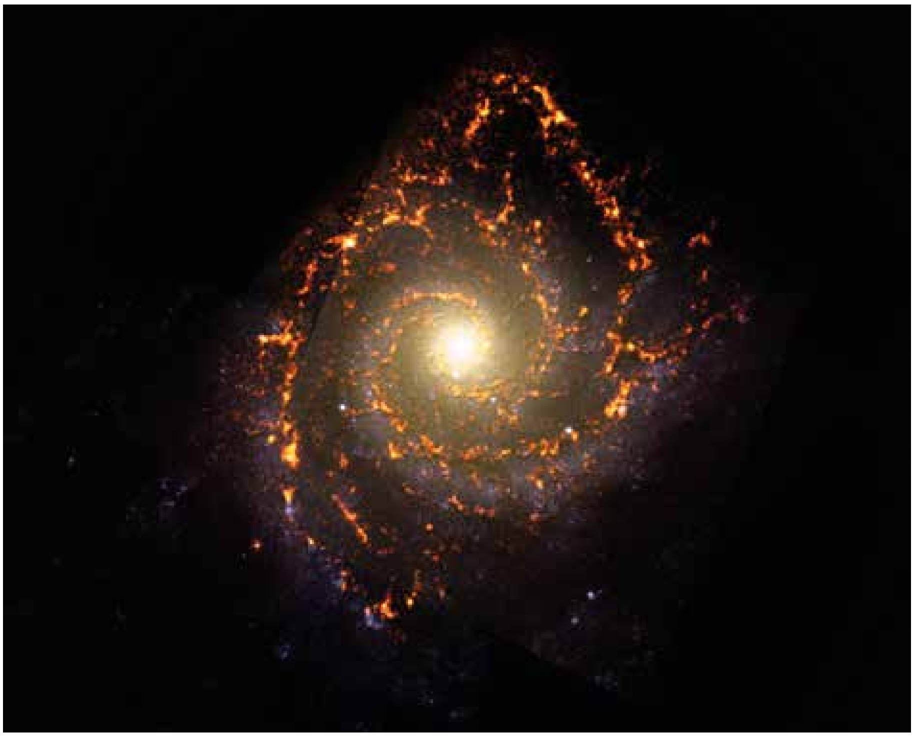
Gas: the fuel for making the stars in galaxies

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

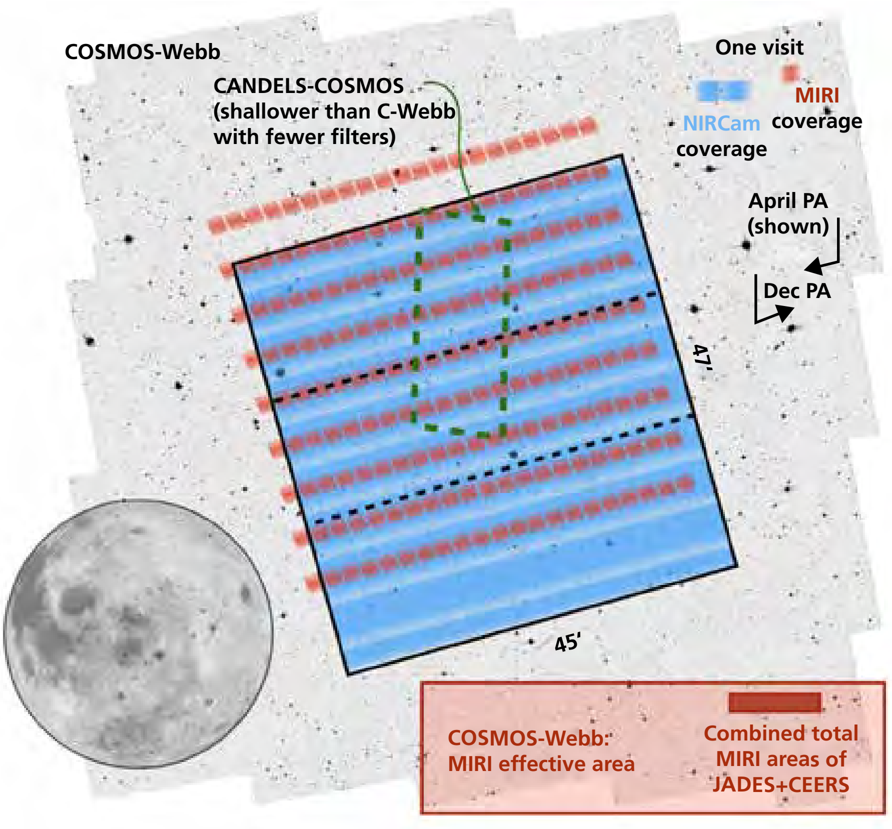
In order to understand galaxy formation, it is crucial to understand the ways in which gas cools and condenses at the centers of gravitational potential wells which are due to the presence of dark matter, gets transformed into molecular gas, and finally forms stars. Understanding the processes that suppress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

The galactic and circum-galactic gas cycle is far from understood. In order to improve our understanding, we need to find ways of studying all the different varieties of gas: dense molecular gas, neutral (atomic), and ionized gas. This requires a wide range of techniques, from submillimeter observations of molecular lines to studies

Fig. II.2.2: For comparatively nearby galaxies in particular, high-resolution observations yield many structural details, which can then be used to make deductions about galaxy properties in general. This is an image of NGC 628 (=Messier 74), a galaxy with pure grand design spiral morphology. NGC 628 is shown here as a composite of data taken with ALMA (orange/red) and with the Hubble Space Telescope (HST). The image is part of the PHANGS ("Physics at High Angular Resolution in Nearby GalaxieS") project which is led by MPIA's Eva Schinnerer. The project makes use of detailed data for nearby galaxies to study how star formation in a galaxy depends on that galaxy's size, age, and internal dynamics.



Credit: ALMA (ESO/NAOJ/NRAO)/PHANGS, S. Dagnello (NRAO)



Credit: J. Kartaltepe / RIT. C. Casey / UT Austin. A. Koekemoer / STScI

Fig. II.2.3: Just like other researchers world-wide, the astronomers from the GC department are preparing for exciting first results from the JWST, which was launched in December 2021. The COSMOS-Webb survey, in which MPIA is a prominent member thanks to Knud Jahnke and his group, will be the largest single programme in JWST's first year of operations. It will map 0.6 square degrees of the sky – about the area of three full moons–using JWST's Near Infrared Camera NIRCam. Simultaneously, a smaller 0.2 square degrees area will be explored with the Mid Infrared Instrument MIRI. In a total of more than 200 observing hours, the survey is meant to register about 500 000 galaxies, including high-resolution imaging in different spectral regions of the near-infrared, and another 32 000 galaxies in the mid-infrared. The aim of the survey is to map the earliest structures in the universe.

of UV absorption lines caused by hot gas. Facilities such as the IRAM NOEMA Interferometer, ALMA, and large optical telescopes to study quasar absorption lines are crucial tools for this research.

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

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

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

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

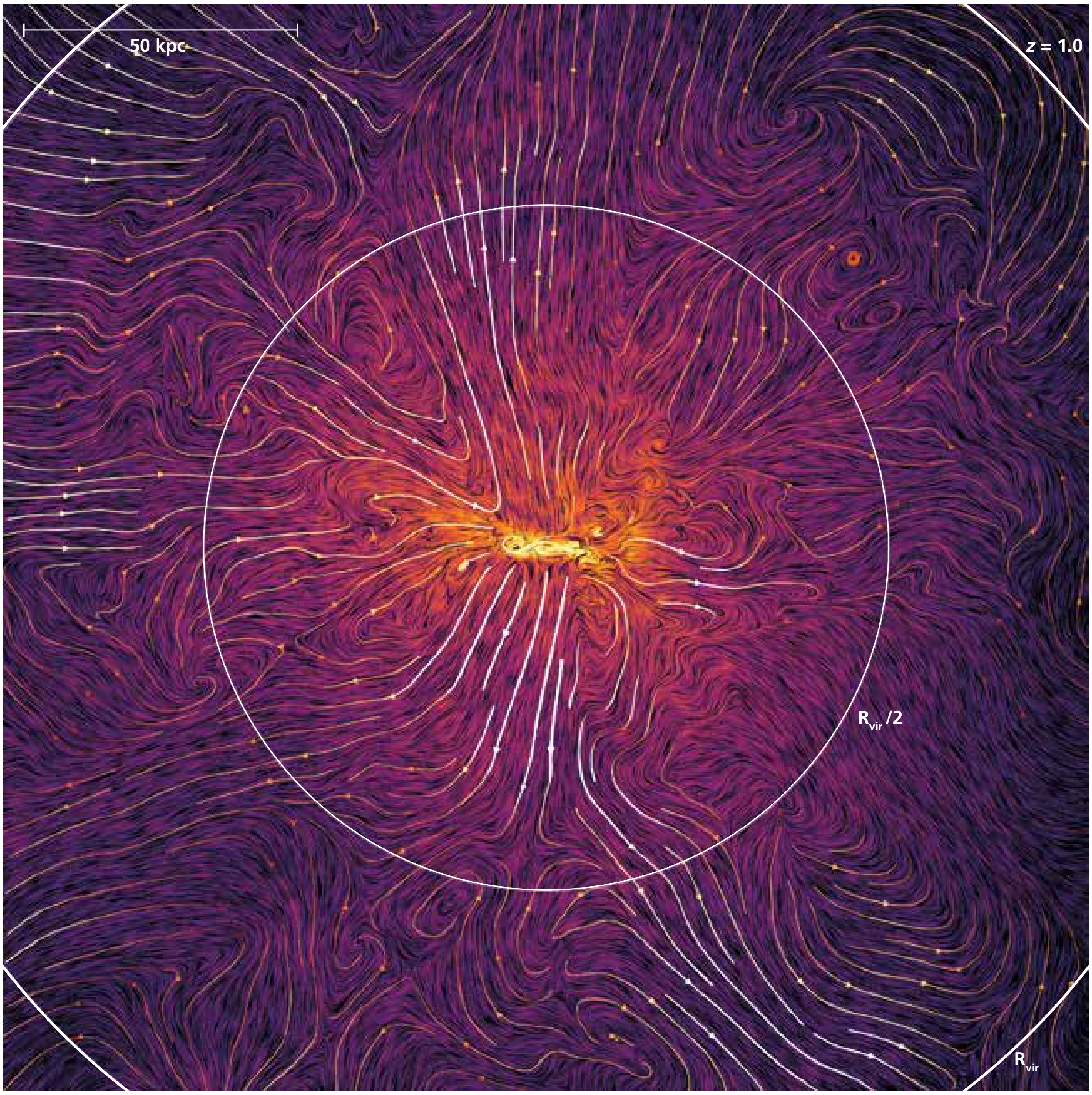
Asking the right questions

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

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

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

Fig. II.2.3: Simulations like Illustris TNG50, created by the TNG Collaboration in which the Galaxies and Cosmology Theory group led by Annalisa Pillepich plays a leading role, make it possible to follow the evolution of a model universe from the Big Bang to the present. A key challenge is the disparity of scales: simulating a representative sub-region of a vast cosmos while resolving structural details within the separate galaxies involved. The image shows gas flows in the halo of a single galaxy simulated with TNG50, which is similar in mass to a so-called Lyman-break galaxy. Streamlines of gas motion are overlaid on a line-integral convolution image of gas density modulated by its velocity field. Outflows emerge collimated from the central galaxy traverse half the virial radius (dotted circle), producing small-scale vortical motions as well as a large-scale, circulatory, galactic-fountain type flow confined within the halo virial radius.



Credit: TNG Collaboration

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

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

From observations to simulations

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

- we study galaxies in the present-day Universe, including our own Milky Way, making the most of the level of detail afforded by observations in our direct cosmic neighborhood.
- we study galaxies at earlier cosmic epochs directly by observing very distant objects (corresponding to high cosmological redshifts z); after all, astronomy always means observing the past: when light from a distant galaxy takes, say, 10 billion years to reach us, our present observations show us that galaxy as it was 10 billion years ago, affording us a glimpse into the distant past.
- we develop physical models and progressively improve both them and our understanding of galaxy formation by testing their outcome against observations. The models developed and analyzed at MPIA follow the co-evolution of dark matter, stars, cosmic gas and supermassive black holes starting from the initial conditions shortly after the Big Bang and require computing investments of tens of hundreds of million computing hours using thousands of computers.

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

Collaborations and initiatives

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

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

II.3 Research Overview

Atmospheric Physics of Exoplanets (APEx)

Director: Dr. Laura Kreidberg

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

Characterizing diverse atmospheres

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

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

A diversity of challenges

Exoplanet atmosphere characterisation provides major challenges on multiple fronts: from pushing detectors beyond their design limits to search for the tiny signal of atmospheric absorption, to modelling atmospheric

Fig. II.3.1: Happy APExers at the first-ever department retreat; September 2021 in Deidesheim.

Credit: E. Nasedkin

physics and chemistry over orders of magnitude in time and distance. Tackling these challenges requires close collaboration between experts, and progress in the field will be greatly accelerated with an entire department devoted to these topics. Hiring has been a major focus for the first years of the department, and APExers were glad to have their first in-person retreat in 2021 (Fig. II.3.1).

Already, APEx astronomers are leading observing and modeling initiatives with state-of-the-art facilities and tools. These include Hubble and Spitzer observations of lava worlds and ultra-hot Jupiters, interpretation of some of the first exoplanet spectra directly measured by K-band interferometry, and 3D modeling of atmospheric dynamics. A recent highlight is the measurement of a full-orbit phase curve for an ultra-hot Jupiter, the planet WASP-121b (shown in Fig. III.3.2). Hubble observations of the planet revealed changes in the temperature structure between the dayside, which is illuminated by the star, and the cold nightside. The dayside has a temperature inversion in the stratosphere, where the temperature increases with height. The stratosphere is heated on the dayside by the intense stellar radiation, but not on the nightside. This measurement is the first detection of such diurnal variations on an exoplanet.

Looking forward, APEx scientists will be working with even better data from the James Webb Space Telescope, which successfully launched on 25 December, 2021. Webb's larger mirror and broader wavelength coverage will open the door to studying a wider variety of planets in greater detail than ever before. The APEx department is leading three observing proposals during the first cycle of Webb observations, so will have first access to the data from this revolutionary facility.

Instrumentation

Another focus for the APEx department is instrumentation. Exoplanet detection alone is a challenging proposition, and characterisation is more difficult still. Planets are at least 10 000 times fainter than their host stars, and are best studied with purpose-built instrumentation.

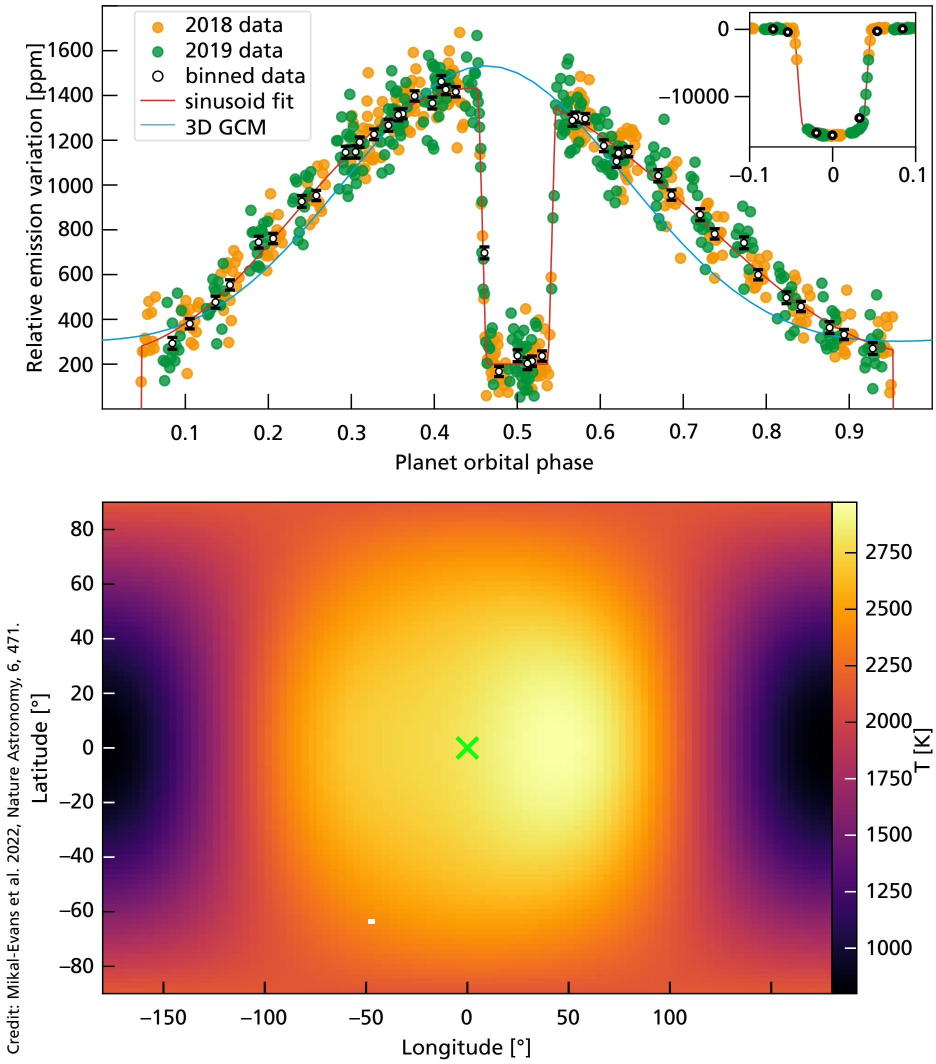


Fig. II.3.2: The thermal phase curve of the ultra-hot Jupiter WASP-121b *(top panel)* and climate map *(bottom panel)*. The extreme heat on the planet's dayside – over 2500 Kelvin – causes a temperature inversion.

Many of the advances in exoplanet characterisation are the direct result of new instruments and observing capabilities. APEx is therefore investing in two ground-based instrumentation projects that will provide unprecedented capability to study exoplanet atmospheres.

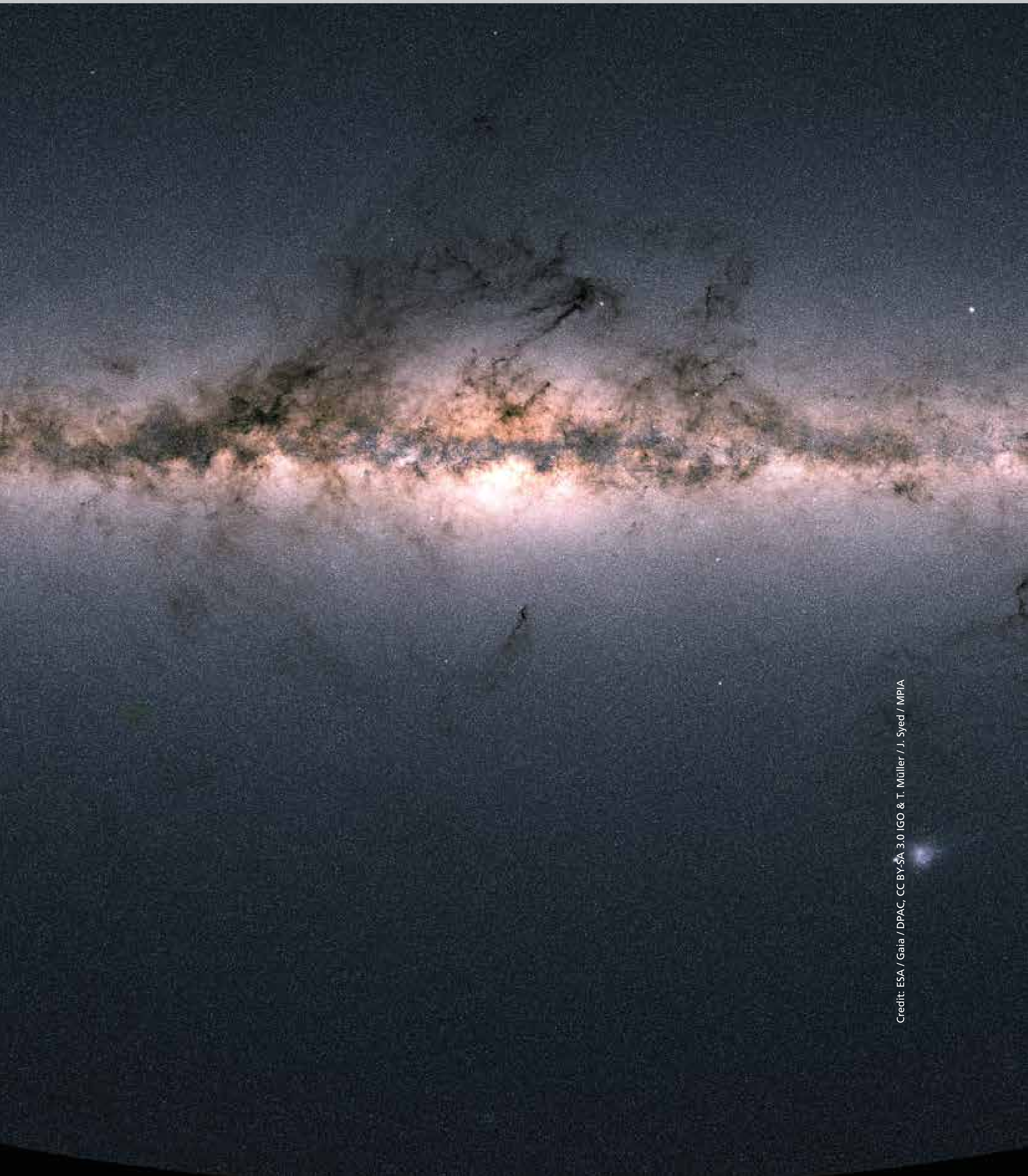
One of these is the METIS instrument, a first light instrument for ESO's upcoming Extremely Large Telescope (ELT). METIS will be capable of both direct imaging and high-resolution spectroscopy, and can detect thermal emission from Earth analogs around the nearest stars. It will also be able to measure 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 second instrumentation project is the upgrade to the Very Large Telescope GRAVITY instrument. GRAVITY is the first K-band interferometer ever built, and can spatially resolve planets from their host stars without the need for a coronagraph. The resulting exquisite spectra provide the most precise constraints to date on fundamental atmospheric properties like the carbon-to-oxygen ratio. The upgraded instrument, GRAVITY+, will have higher sensitivity and contrast thanks to improved adaptive optics, and it will be capable of searching for new planets including Jupiter analogs. Known planets will also be studied in even greater detail, including second-order effects like weather.

APEx also recently joined the ANDES Collaboration. ANDES is a second-light ELT instrument that will be 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.

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

III. Science Highlights



III.1 Highlights

A blazing nearby super-Earth

A hot super-Earth in our neighborhood promises to be a suitable candidate to test rocky planet atmosphere models

During the last two and a half decades, astronomers discovered thousands of exoplanets made of gas, ice, and rock. Only a few of them are Earth-like. Astronomers of the CARMENES consortium led by Trifon Trifonov have discovered a hot rocky super-Earth orbiting the nearby red dwarf star Gliese 486. Despite its small separation from the parent star, the planet designated Gliese 486b possibly has retained a part of its original atmosphere. Therefore, Gliese 486b is uniquely suited to examine its atmosphere and interior with the next generation of space-borne and ground-based telescopes.

With the advent of efficient exoplanet-hunting facilities, the numbers of newly discovered worlds outside the Solar System quickly rose to the thousands. By combining different observing techniques, astronomers have determined planetary masses, sizes, and even bulk densities, allowing them to estimate their internal composition. The next goal to fully characterize those exoplanets similar to Earth by studying their atmospheres is much more challenging. Especially for rocky planets like Earth, any such atmosphere consists of a thin layer, if it exists at all. As a result, many current atmospheric models of rocky planets remain untested.

Planetary atmospheres must meet specific prerequisites to observe them with next-generation observatories. At a distance of only 26 light-years, scientists of the CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs) consortium now have found a planet that perfectly satisfies these specifications for rocky planets. The newly discovered planet designated Gliese 486b is a super-Earth with a mass 2.8 times that of our home planet. It is also 30% bigger than Earth. The scientists employed both transit photometry and radial velocity spectroscopy to obtain their results. The proximity of this exoplanet permits studying it in more detail with powerful telescopes such as the James Webb Space Telescope and the future Extremely Large Telescopes.

The astronomers calculated the planet's mean density from the mass and radius measurements. They conclude that its composition is similar to Venus and Earth, including a metallic core. Anyone standing on Gliese 486b would feel a gravitational pull that is 70% stronger than what we experience in our world.

Fig. III.1.1: Artistic impression of the surface of the hot super-Earth Gliese 486b. With a temperature of about 700 Kelvin (430 °C), the astronomers of the CARMENES collaboration expect a Venus-like hot and dry landscape interspersed with glowing lava rivers. Gliese 486b possibly has a tenuous atmosphere.

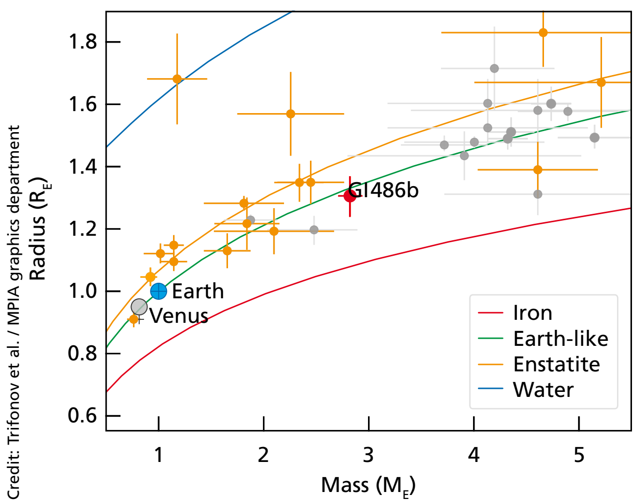


Fig. III.1.2: The diagram provides an estimate of the interior compositions of selected exoplanets based on their masses and radii in Earth units. The red marker represents Gliese 486b, and orange symbols depict planets around cool stars like Gliese 486. Grey dots show planets hosted by hotter stars. The colored curves indicate the theoretical mass-radius relationships for pure water at 700 Kelvin (blue), for the mineral enstatite (orange), for the Earth (green), and for pure iron (red). For comparison, the diagram also highlights Venus and the Earth.

Gliese 486b revolves around its host star Gliese 486 on a circular trajectory within 1.5 days and at a distance of 2.5 million kilometers. One rotation takes just as long, so the same side always faces the star. Although Gliese 486 is much fainter and cooler than the Sun, the irradiation is so intense that the planet's surface heats up to at least 700 Kelvin (approx. 430 °C). In this sense, Gliese 486b's surface probably looks more like Venus than Earth, with a hot and dry landscape interspersed with glowing lava rivers. However, unlike Venus, Gliese 486b possibly only has a tenuous atmosphere, if any. Model calculations may be consistent with both scenarios because stellar irradiation tends to evaporate atmospheres. At the same time, the planet's gravity helps to retain it. Figuring out the balance of those contributions is difficult.

The discovery of Gliese 486b was a stroke of luck. A hundred degrees hotter, the planet's entire surface would be lava. Its atmosphere would consist of vapourised rocks. If it were a hundred degrees colder, it would be unsuitable for follow-up observations.

The future measurements that the CARMENES team has in mind exploit the orbital orientation, which causes Gliese 486b to cross the surface of the host star from our point of view. Whenever this happens, a tiny fraction of the stellar light shines through the thin atmospheric layer before it reaches Earth. The various compounds absorb light at specific wavelengths, leaving their footprint in the signal. Using spectrographs, the astronomers split the light according to wavelengths and look for absorption features to derive the atmospheric composition and dynamics. This method is also known as transit spectroscopy.

A second spectroscopic measurement, called emission spectroscopy, is planned when parts of the illuminated hemisphere become visible like lunar phases during Gliese 486b's orbit until it vanishes behind the star. The spectrum contains information on the bright, hot planetary surface. The results will help the scientists understand how well rocky planets can hold their atmospheres, figure out the atmospheres' compositions, and how they influence the energy distribution on the planets.

The CARMENES consortium comprises eleven research institutions in Spain and Germany. Its purpose is to monitor some 350 red dwarf stars for signs of low-mass planets using a spectrograph mounted at the 3.5 m Calar Alto telescope (Spain). This study includes additional spectroscopic measurements to infer Gliese 486b's mass. The scientists obtained observations with the MAROON-X instrument at the 8.1 m Gemini North telescope (USA) and retrieved archival data from the 10 m Keck telescope (USA) and the ESO 3.6 m telescope (Chile).

Photometric observations to derive the planet's size stem from the TESS (Transiting Exoplanet Survey Satellite) spacecraft (NASA, USA), the MuSCAT2 (Multicolour Simultaneous Camera for studying Atmospheres of Transiting exoplanets 2) instrument mounted at the 1.52 m Telescopio Carlos Sánchez at Observatorio del Teide (Spain), and the LCOGT (Las Cumbres Observatory Global Telescope), among others.

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T. Trifonov, J. A. Caballero, J. C. Morales, A. Seifahrt, I. Ribas, A. Reiners et al., "A nearby transiting rocky exoplanet that is suitable for atmospheric investigation" in Science, Vol. 371, Issue 6533, 1038 (2021), DOI: 10.1126/science.abd7645

III.2 Highlights

The most distant radio beacon in the early universe

Quasars are the highly luminous centers of galaxies powered by supermassive black holes actively accreting matter. Using various telescopes, astronomers have found the most distant radio-bright quasar currently known. Telescopes see this quasar designated P172+18 when the Universe was only 780 million years old. P172+18 is one of the fastest-growing supermassive black holes known to date, emitting about 580 times as much energy as the entire Milky Way. Such distant radio-loud quasars are essential for studying the formation and evolution of massive galaxies and black holes in the early universe.

Quasars are among the brightest objects in the Universe. Therefore, astronomers can study them in detail at large cosmological distances. Although first discovered in 1963 by measuring radio waves, only 10% of quasars are radio-loud, i. e., shine particularly bright at radio frequencies. However, astronomers struggle to explain this small fraction and whether it also holds for the earliest cosmic epochs. Only three radio-loud quasars with redshifts (z) of six or more were known, with the most distant being at $z = 6.2$. Redshift is the measure cosmologists use to indicate large distances of objects caused by the cosmic expansion that moves the electromagnetic

Fig. III.2.1: Artistic impression of a quasar like P172+18. A central supermassive black hole attracts neighboring gas. It swirls into the black hole via an accretion disk, where the gas attains high velocities. Friction heats the gas to very high temperatures, producing intense UV radiation. Twisted magnetic fields confine focused jets above and below the accretion disk, which carry away a fraction of the hot, ionized gas. These jets are a source of intense radio emission.

Credit: ESO / M. Kornmesser

spectrum towards longer wavelengths. Redshift directly corresponds to the age of the Universe at which, e. g., a quasar is observed.

An international group of researchers has discovered a new record holder for the most distant radio source. Eduardo Bañados (MPIA) and Chiara Mazzucchelli of the European Southern Observatory (ESO) in Chile and former MPIA PhD student headed the collaboration. The scientists found the quasar designated P172+18 at redshift $z = 6.82$. It corresponds to an era when the Universe was just 780 million years old, about 100 million years earlier than the previous record holder.

However, the observations are not just for chasing distance records. Distant radio-loud quasars at the beginning of the evolution of the cosmos also serve as beacons to study material that lies between Earth and the quasars. Because gas at different redshifts will leave its fingerprint on the spectrum of quasars, astronomers can use the pattern to determine the gas density and its distribution in the early universe.

The supermassive black hole in the center provides the gravity that attracts the surrounding gas and causes it to plunge inside. An accretion disk forms in the process, over which the gas swirls into the black hole. Its friction causes heating to such high temperatures that it glows particularly brightly in UV light. This process releases as much radiant energy per second as 580 times that of the entire Milky Way.

P172+18's black hole mass amounts to about 70 times the mass of its counterpart in the Milky Way center, and it is still rapidly growing. The measurements indicate that this quasar hosts one of the fastest accreting supermassive black holes known today. The resulting radiation emitted by the accretion disk becomes so intense that it pushes on the collapsing gas and gradually slows down the inflow.

The radio emission measured by the researchers with NRAO's Karl G. Jansky Very Large Array (VLA) points to a jet accelerating ionized gas in a narrowly focused beam to near the speed of light. Such jets also serve as a valve that relieves some of the pressure built up by the accretion process. A comparison with 20-year-old data suggests that P172+18 has recently lost radio luminosity. However, only further measurements can help determine conclusively whether this finding has anything to do with a weakening jet and a reduction in accretion activity.

Originally, P172+18 was only one of many quasar candidates identified by an evaluation of the Pan-STARRS survey. Ultimately, however, the team needed precise observations with infrared telescopes to determine the distance of the quasar and the black hole properties. Astronomers employ infrared cameras and spectrographs to capture the light objects in the early Universe emit. To achieve the necessary precision, the researchers combined observations from the Magellan Baade Telescope at Las Campanas Observatory (Chile), the

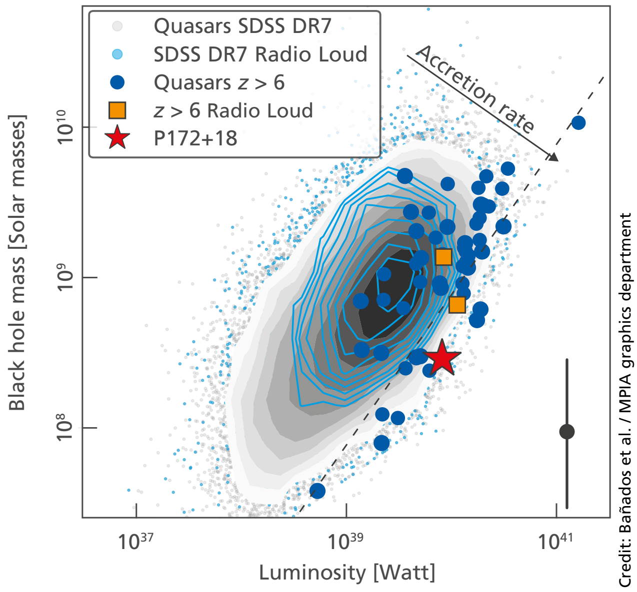
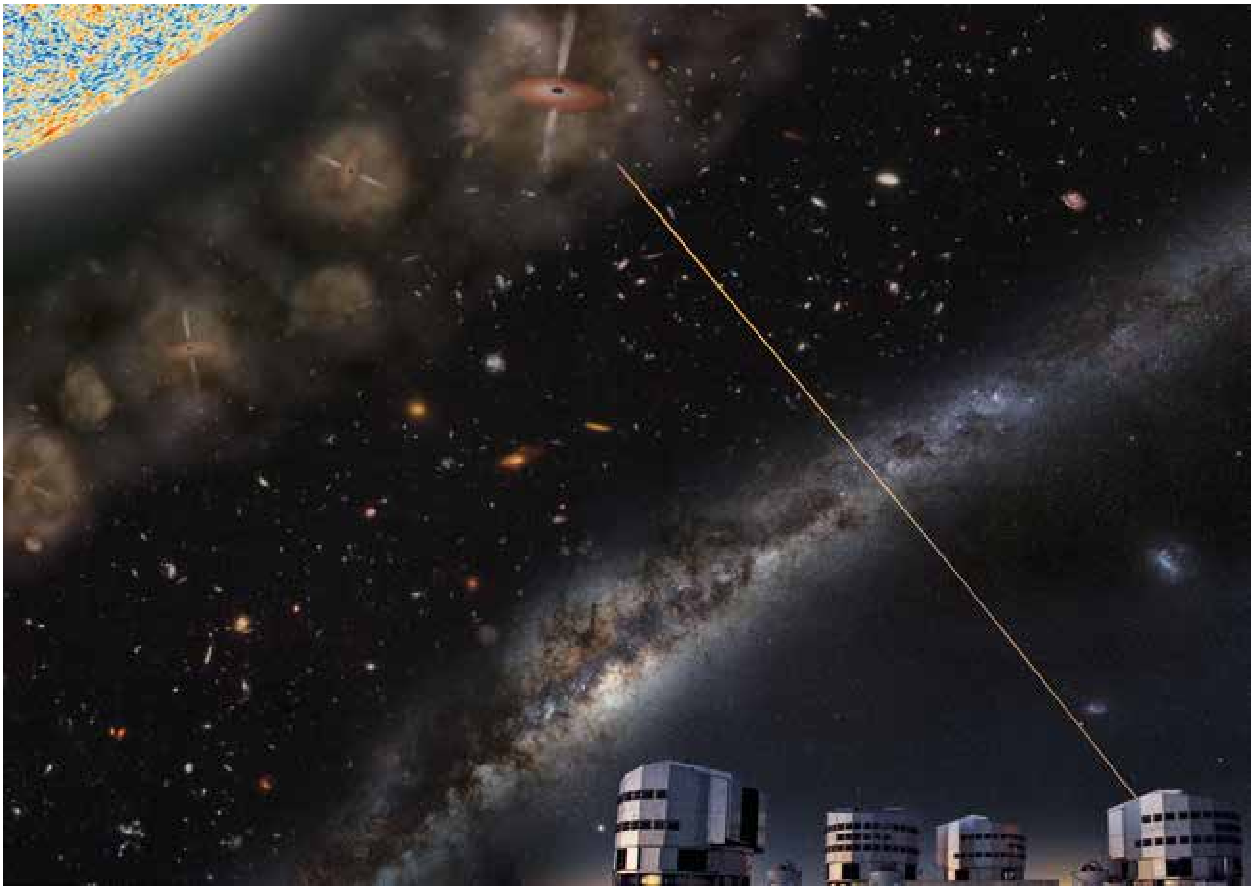


Fig. III.2.2: The graph provides a synopsis of quasar properties selected from the Sloan Digital Sky Survey (SDSS, grey dots). It shows black hole masses given in solar units combined with luminosities. The diagram shows radio-loud quasars with light blue dots and contours. Dark blue dots (all quasars) and orange squares (radio-loud) depict distinct quasars with redshift beyond six. A red star marks the position of P172+18. The black symbol to the bottom right indicates the systematic uncertainties. The dashed line represents the range where the luminosity surpasses a limit (Eddington limit). The accretion becomes unstable and gradually declines. The diagram reveals that P172+18 is one of the fastest accreting quasars in the early universe.

Nordic Optical Telescope (NOT) on La Palma (Spain), the Keck telescope in Hawaii (USA), the Very Large Telescope (VLT) of the European Southern Observatory (ESO Chile) and the Large Binocular Telescope (LBT) on Mount Graham (USA).

While studying the radio data, the researchers discovered another radio source in the vicinity of P172+18. Still, they have not yet determined its redshift and distance. Due to the quasars' spatial distribution, the probability of another chance hit in the immediate vicinity is very low. If it were a physically connected source, their separation projected against the imaginary celestial sphere would be about 400 000 light-years. This range corresponds to roughly twice the distance between the Milky Way and the Small Magellanic Cloud. The team led by Bañados is now trying to confirm whether these two sources are physically associated. If true, it would indicate that this is one of the first galaxy overdensities in the early universe.

The discovery of early galaxy grouping would be spectacular because exploring the formation of structures in this epoch is just beginning. The idea is that clouds of neutral hydrogen initially assemble, which then develop into galaxies, potentially hosting quasars. Systematic research into such hydrogen clouds during the first billion years of the Universe is still a long way off, but it is, in principle, possible. For this purpose, radio-loud quasars



Credit: MPIA graphics department

Fig. III.2.3: The illustration depicts observations of the most distant radio source currently known, the quasar P172+18. Telescopes see it just 780 million years after the Big Bang. The radiation emitted by quasars during the first hundreds of millions of years after the Big Bang helps astronomers investigate the matter in the foreground. Astronomers can study the distribution of neutral hydrogen gas clouds in the early universe using radio wave emission of radio-loud quasars with jets like P172+18 as background sources. Those clouds may be the precursors to galaxies and help probe early galaxy formation and clustering depending on cosmic age.

serve as background sources for researchers to detect these clouds. Astronomers still don't know why different quasars exhibit such a wide variety of radio emissions. Studying them at the earliest possible cosmic epochs can reveal how supermassive black holes grow. It is one of the biggest mysteries of astrophysics that still needs to be solved.

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Eduardo Bañados et al., "The Discovery of a Highly Accreting, Radio-loud Quasar at $z = 6.82$" in The Astrophysical Journal, Vol. 909, 1 (2021). DOI: 10.3847/1538-4357/abe239

III.3 Highlights

Why asteroids are born big

Why do asteroids in the solar system have the sizes we observe? Hubert Klahr and Andreas Schreiber have found an answer to that fundamental question. Turbulence played a crucial role in the birth of planets and planet precursors in our Solar System 4.5 billion years ago. This process helped bring together pebble-like objects to form larger aggregates known as planetesimals and set a minimal mass and thus a minimal size for the resulting objects. From this model, the two researchers can predict the peak in the size distribution of the remaining objects of this type in the present Solar System, namely the asteroids and cKBOs (classic Kuiper Belt Objects).

In a way, the asteroid belt between Mars and Jupiter and the Edgeworth-Kuyper belt beyond the orbit of Neptune are like cosmic museums: Both contain small bodies that represent an intermediate state of planet formation within our Solar System. Hubert Klahr, head of the Planet and MPIA Star Formation Theory Group, and Andreas Schreiber, his PhD student and later postdoctoral researcher, have shown how fundamental physics determined the size of the original asteroids. It is considered a fundamental length scale within the early solar system. The result rewrites a chapter on planet formation around the Sun and makes specific predictions that space probes can test in the outer solar system.

An ancient length-scale mystery

Both asteroids and comets are what remains of so-called planetesimals. They are solid objects, large enough to be bound by their own gravity, formed roughly 4.5 billion years ago when a disk of gas and dust still surrounded the Sun. Many planetesimals went on to eventually form the current planets. However, in the asteroid belt, the gravitational influence of nearby Jupiter kept planetesimals from clumping together. In the outer solar system, beyond Neptune, planetesimals simply did not encounter each other frequently enough to bond. That is why, in those regions, we still have these objects around, which provide us with a glimpse into the early solar system. We call them asteroids and cKBO, dependent on the location we find them today, and some of them, which are in a co-orbit with Jupiter, we call Trojans.

The intervening 4.5 billion years did not leave the asteroids untouched. The asteroid belt is much emptier than science fiction movies make it seem. Collisions are rare and happened over billions of years, leaving numerous smaller fragments behind. Those fragments then move on fairly similar orbits, spreading out over time. About a quarter of all known asteroids belong to a family – a group originating from the same collision.

By plotting the orbital parameters of known asteroids, astronomers can estimate which objects populate such a cloud of fragments. Take the 500-meter-sized asteroid 101955 Bennu, visited by the NASA spacecraft OSIRIS-Rex (Kevin Walsh), to bring some of its material back to Earth. Bennu is believed to be a fragment of a much larger asteroid and is possibly a member of the Polana or Eulalia family of asteroids.

However, in 2017, a thorough asteroid family tree analysis found 17 asteroids that apparently had not undergone any collision at all. Hence, they are still in the same primordial state as they would have been when they formed. The primordial asteroids, and thus presumably the original planetesimals, have a very narrow size distribution. Objects with a diameter of around 100 kilometers are far more common than larger or smaller objects, following a so-called Gaussian or normal distribution. But why the 100 kilometers? What is unique about this scale?

The challenge of forming large clumps

Hubert Klahr and his colleagues have spent the past decade trying to understand how planets form. He and Schreiber were able to make significant progress and solve the question of the preferred 100-kilometer scale simultaneously.

The broad-brush story of planet formation has been known for a long time. Take a popular astronomy book from the 1970s, and one can read how material was left over from the initial disk of gas and dust surrounding the young Sun and how that matter clumped together to form planets. However, the details have long been surprisingly difficult. The dust in the gas disk surrounding a newborn star can indeed clump together to form what astrophysicists call pebbles – clumps between a few millimeters and a few centimeters in size.

Nevertheless, moving from there to kilometer-sized objects has been troubling planet-formation researchers for decades. As pebbles grow, several things happen: Pebbles become more likely to fracture as they collide rather than stick together. For a while, researchers had hopes that water ice on pebbles might help them cling together. That did not turn out to be very convincing either, not least because ice at very low temperatures is not all that sticky.

Overall, the conventional scenarios continue to have a time-scale problem. Since the surrounding gas rotates more slowly than needed for a solitary solid object orbiting a star, larger pebbles tend to drift inward and eventually fall into their star. For small growth rates, the objects in question would have ended up inside their stars before reaching the necessary size. Only objects larger than about one meter can escape that fatal drift. They become largely independent of the buffeting by the surrounding gas. However, how can bodies reach that size?

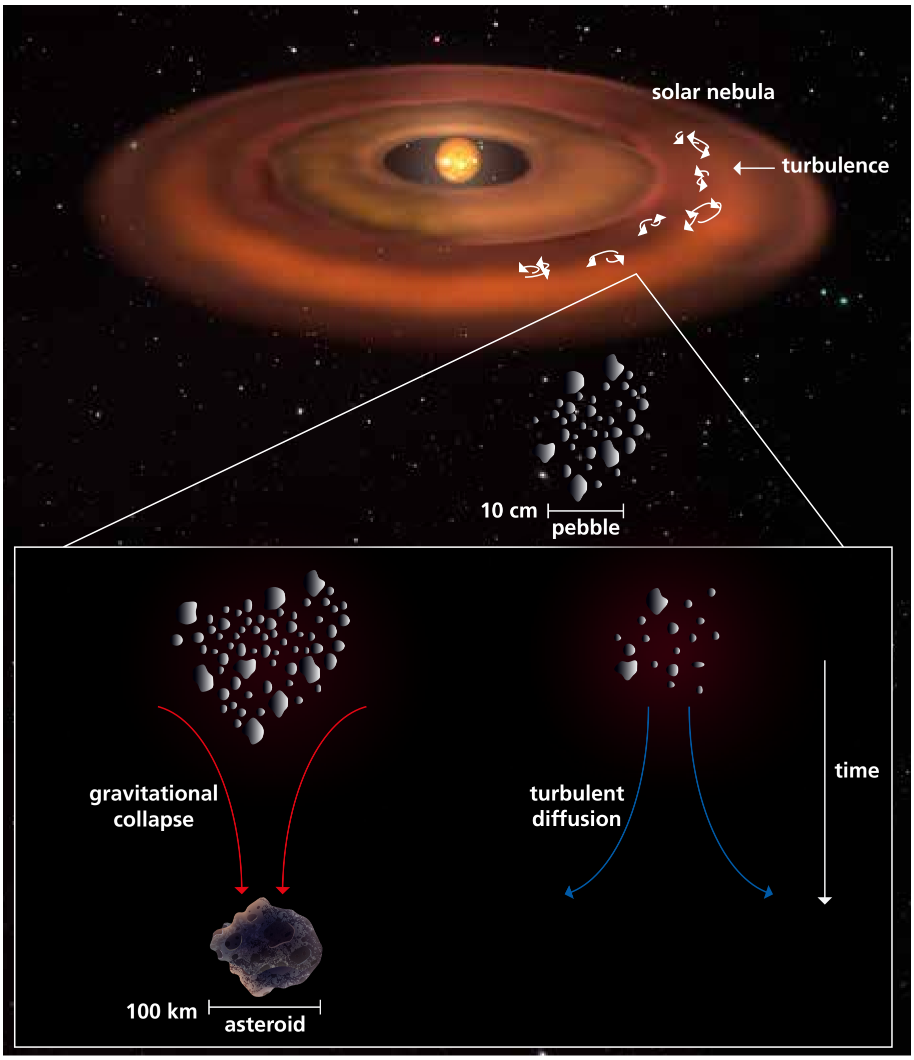
Fig. III.3.1: Planetesimals (Asteroids, Comets, KBOs, etc.) form by gravitational collapse of pebble clouds made of ice and dust. The density inside such a cloud must surpass a critical value to prevent the solar tides from disrupting it. The strength of turbulent diffusion sets the minimal mass that can collapse. If the mass is too low, then the cloud is getting dispersed. Only if the cloud contains enough mass to form a 100-kilometer-sized body gravity wins over turbulent diffusion.

Turbulence to the rescue

The Klahr team has been tracking the role of turbulence – chaotic flows within gas or another fluid – as a solution to the larger-than-pebbles problem. Observations show that gas flow is turbulent in protoplanetary disks, with chaotic local variations in gas speed. Without turbulence, dust and pebbles would form a disk as razor-thin as Saturn's rings. Instead, observations show dust is present throughout the thicker gas disk surrounding young stars.

On larger scales, turbulent gas motion in protoplanetary disks can create regions of greatly increased pebble and dust concentrations. Intermittently, such environments can become veritable pebble traps. In such aggregates, pebbles can accumulate with sufficient total mass for them to bind together by their mutual gravity leading to the formation of larger objects on the required much shorter time scales.

First indications of the turbulence's role in planet formation came from numerical simulations and the comparison with detailed observations of the protoplanetary disks around new stars. Earlier simulations showed that



Credit: H. Klahr, A. Schreiber / MPIA, J. Neidel / MPIA graphics department turbulence forces pebbles together and leads relatively quickly to the formation of planetesimals. Simulations are one thing. Klahr and Schreiber set out to better understand the underlying physical laws of what was happening in those simulations and presumably around young stars.

The physics behind the turbulent formation of planetary embryos proved surprisingly straightforward and has fundamental similarities to how stars form: Astronomers had found a minimum mass for a newborn star as well. The reason is the internal pressure of the gas clouds that give birth to young stars. For gravity to overcome that pressure and pull the gas together into a compact object, a newly forming star needs to reach a certain mass. This mass is known as the Jeans mass and depends on the gas density and the temperature.

Klahr and Schneider found a new kind of Jeans mass for the formation of planetesimals. In this case, the turbulent motion of gas and dust produces the internal pressure counteracting gravity.

Setting the scales for planetesimals

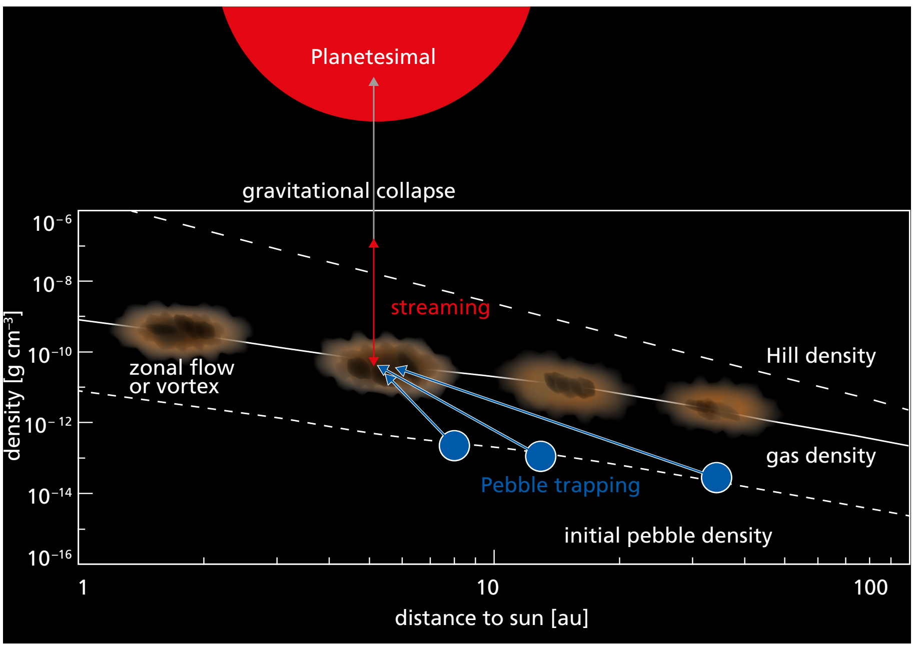
This new fundamental scale depends only on the local strength of the turbulence, which in turn depends on how the structure of the gas disk changes as one moves farther away from the central star. If gas pressure drops sufficiently fast with distance, the so-called "streaming instability" will unavoidably produce turbulent motions of the gas and dust. Instead of sinking quietly towards regions of larger pressure, i.e., towards the central stars, pebbles move chaotically, stirring the surrounding gas.

For most regions within our Solar System, the turbulent-pressure Jeans mass of a pebble cloud corresponds to planetesimals of a size of around 100 kilometers. Pebble clouds of lower mass are less likely to collapse. They would need a rare random fluctuation to bring them together all at once. Larger clouds are less likely to form, as clouds should collapse as soon as they exceed the critical mass. Thus, both smaller and larger planetesimals are possible but naturally much rarer.

Finally, this process was a suitable candidate for the physics behind the universal Solar-System length scale of primordial asteroid sizes – a limiting mass for forming planetesimals.

Klahr's and Schreiber's calculations also make a prediction for remnants of the early planet-formation process in the outer Solar System. Based on what we know from the properties of our Sun's protoplanetary disk, the size of primordial objects formed in that outer region shrinks to 10 km at a hundred times the Earth-Sun distance. It would be a worthy goal of a future outer system space mission to study how the characteristic size of so-called Kuiper Belt Objects decreases with increasing distance from the Sun.

Fig. III.3.2: Dust and ice pebbles in the solar nebula contribute less than 1% of the mass. The rest is hydrogen and helium. In this schematic graph, we show the initial local density in pebbles as a function of distance to the sun compared to the gas density and the critical density (Hill density) to which pebbles have to condense before a cloud of pebbles can withstand disruption by solar tides. Pebbles may sediment and drift towards the star but can be trapped in "zonal flows", acting as vortices and pressure bumps. As a result, a self-gravitating pebble cloud can form. If the turbulent diffusion inside this pebble cloud is low enough compared to its mass, it can collapse into one or several planetesimals of 10 to 100 kilometers in size.



Credit: H. Klahr, A. Schreiber / MPIA, J. Neidel / MPIA graphics department

Visits to a planetary museum

Comets visiting us from that outer part of the solar system, the Edgeworth-Kuiper belt, are not likely to be in pristine shape. Simulations suggest that they will unavoidably have undergone several collisions since the beginning of the Solar System. A direct mission into the Edgeworth-Kuiper Belt, where collisions are less likely, should be able to identify and examine truly pristine and primordial planetesimals.

The New Horizons mission briefly visited such a planetesimal after its Pluto flyby in early 2019. At the time, the object that has since been called Arrokoth [original designation (486958) 2014 MU69] was 45 times as far from the Sun as the Earth, making it the most distant primordial object ever visited. Arrokoth looks like a snowman made of two planetesimals stuck together, one with a diameter of 21 kilometers, the other 15 kilometers. Indeed, the object's surface structure and color hint at an origin from a single, rotating pebble cloud. It fits the size predictions of the pebble model for planetesimals forming at this particular distance from the Sun.

Other primordial planetesimals may exist among the so-called Trojan asteroids, which Jupiter's gravity captured during the birth of the Solar System. Since this era, they have been orbiting the Sun in two groups, one leading and one trailing Jupiter ("Lagrangian points 4 and 5"). NASA's LUCY probe, slated for arrival in 2027, is meant to visit six of those Trojans as part of a 12-year-mission. Based on previous observations, the Trojans apparently stem from different regions of the early solar system – it is as if LUCY is visiting a museum of planet formation!

Understanding planets around other stars

The new prediction for planetesimal sizes also promises a considerable impact on our understanding of the diversity of exoplanets. Perhaps the most outstanding value that the thousands of known exoplanets have for our understanding of cosmic history is providing a statistical sample. Unlike the single case of our Solar System, the many data points for exoplanets allow us to make deductions about how planets form in our galaxy.

If we understand the physics of planet formation, we can predict the probability of forming planetary systems of different kinds – massive planets, smaller planets, narrower or wider orbits. By comparing the actual distribution of planetary systems, we can test our predictions and find out if our simulations are realistic.

There are several ongoing attempts at "population synthesis", that is, at creating ensembles of realistic planetary systems, extracting the frequencies with which certain properties (such as mass ranges or orbital parameter ranges) occur, and comparing the result to observational data. So far, those attempts needed to put in the spatial and size distribution of planetesimals and planetary embryos "by hand" as an educated guess. The new results by Klahr and Schreiber, on the other hand, allow researchers to deduce the planetesimal size distribution for each simulation run from the results for the developing population of pebbles, combined with the results for the gas pressure. Such an approach closes a fundamental gap in the chain of reasoning of population synthesis studies.

The effect of turbulence in allowing larger structures to form will be more significant where the mass concentration within the disk is higher. As the gas within the disk gets depleted – either by falling into the star or being scooped up by what then become gas planets – the capacity for forming larger planetesimals drops. The results allow the researchers running population synthesis models to include the birth of planetesimals and planetary embryos in a simplified way as a function of the gas pressure that is an integral part of the underlying models.

A model with predictive power

The new results have closed a critical gap in the previous knowledge about planet formation. The strength of the new model lies in its predictive power. It can describe when and where planetesimals should form and estimate the sizes of newborn planetesimals. Given that there are competing models, the astronomers need to convince their colleagues that they have indeed found the underlying physics of planetesimal formation. That is where testable predictions can help.

Parts of the planet-formation community favor alternative explanations involving, for instance, the stickiness of ice or "fluffy aggregates" (fluffy silicate flakes) as intermediate steps. For Klahr and Schreiber, it is pretty clear that while there may well be a role for those mechanisms at smaller scales, they have little to contribute to bringing objects into the 100-km region.

Even if collisions supported growth up to 100 km without eventually switching to a gravitational collapse, this method would predict too many asteroids below 100 km. It would also fail to describe the high frequency of binary objects in the Edgeworth-Kuiper belt. Both properties of our Solar System are easily reconcilable with the gravitational pebble cloud collapse.

Hubert Klahr and Andreas Schreiber

H. Klahr, A. Schreiber, "Testing the Jeans, Toomre and Bonnor-Ebert concepts for planetesimal formation: 3D streaming instability simulations of diffusion regulated formation of planetesimals" in The Astrophysical Journal, 911,9 (2021), DOI: 10.3847/1538-4357/abca9b

III.4 Highlights

Citizen science project helps astronomers find rare cosmic jellyfish galaxies

A rare kind of galaxy is at the heart of a new citizen science project. "Cosmological Jellyfish" is part of the Zooniverse platform, where volunteers can contribute to genuine scientific research projects. In the new project, participants look at the results of a cosmological simulation and identify galaxies that look somewhat like jellyfish. The jellyfish-like appearance indicates that the galaxy in question has interacted with gas in a galaxy cluster – which is what the creators of the project, the group of Annalisa Pillepich, want to study further.

Galaxies like our Milky Way galaxy, consisting of millions, billions, or even hundreds of billions of stars, are large-scale building blocks of the Universe. In general, astronomers are confident they have a reliable overall picture of how galaxies have formed over the past 13.8 billion years after the hot Big Bang phase of the Universe. Still, many details need further research – and whenever new observations and powerful simulations become available, there are opportunities to add pieces to the puzzle.

One region of the puzzle that badly needs more pieces is the case of so-called jellyfish galaxies. These galaxies reside in galaxy clusters alongside thousands of other siblings. Besides the galaxies, such clusters also possess thin, hot intergalactic gas. As thin as that gas is, it is enough to make galaxies moving at high velocities through the cluster feel a "headwind".

The missing details of jellyfish formation

Imagine someone on a motorbike, with their hair, or maybe their shawl, streaming behind as they move through the surrounding air. While quickly moving through a cluster, galaxies feel a similar headwind or "ram pressure". The stars in such a galaxy are virtually unaffected, but in extreme cases, the gas within the galaxy can be driven out, trailing the galaxy. The result is a galaxy that looks similar to a jellyfish: a body (made up of the galaxy's stars) with tentacles (gas) streaming behind.

We still have to learn how this works in detail, though: Do jellyfish galaxies appear only in the most massive clusters, or can they even form around the Milky Way? Where and how quickly do the tails form, and how long do they last? What happens to the gas in these tails? How does the stripping process affect the galaxies themselves?

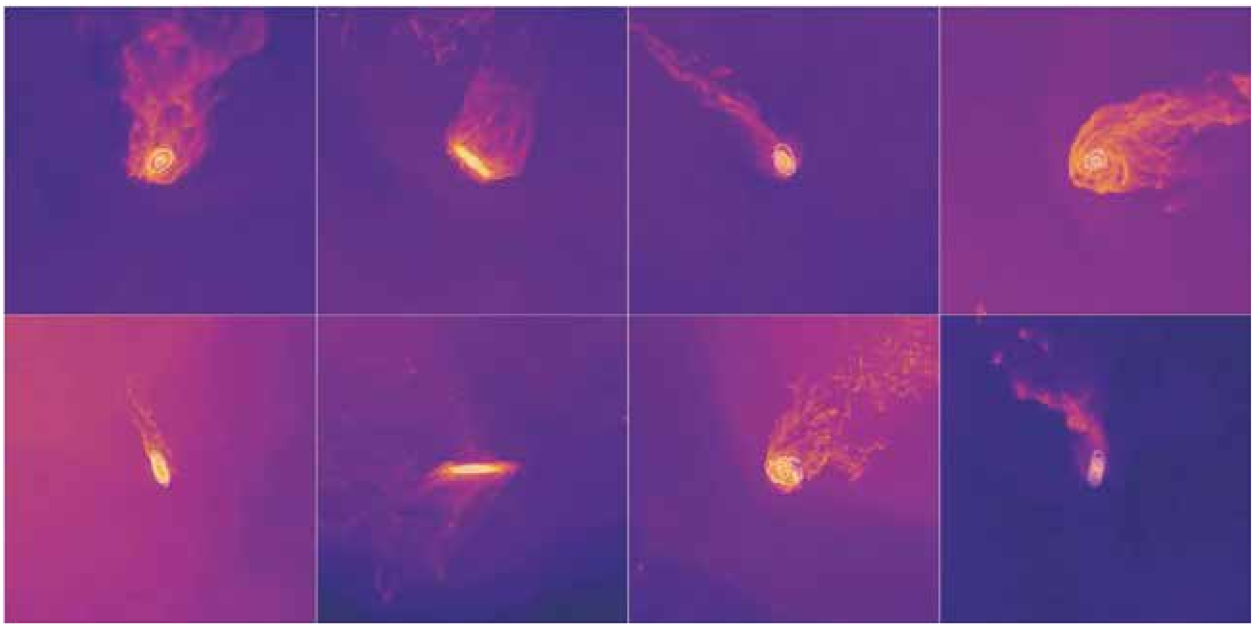


Fig. III.4.1: Eight examples of simulated jellyfish galaxies. The participants work on images like these in the Zooniverse project for classification.

Credit: IllustrisTNG collaboration

Computer simulations to the rescue

Since the processes in question occur over hundreds of millions or even billions of years, observing them in real-time is impossible. However, computer simulations help mitigate this disadvantage and may produce new results. Cosmological simulations create a virtual universe following the same laws of physics as our cosmos. In that model universe, virtual stars and galaxies form, interact, and evolve – and for each galaxy, one can reconstruct its history.

A fundamental problem here is the hugely disparate scales. The physics of how stars evolve takes place on scales of thousands of kilometers. A roughly representative volume of cosmic space is hundreds of millions of light-years across, a factor of one quintillion (one with 18 zeros) larger. No computer simulation has yet managed to simulate individual stars in such a cosmological volume. However, for a few years now, simulations have successfully modeled galaxies in sufficient detail to capture ram-pressure in clusters and how it can turn them into jellyfish galaxies.

Tracking jellyfish in IllustrisTNG

The first large-scale simulations that managed to capture jellyfish creation are part of a suite called IllustrisTNG. There are three different versions of the IllustrisTNG simulation, each with a different size of the cosmic volume, a different resolution, and thousands to hundreds of thousands of galaxies. The two higher-resolution versions of the simulation, known as TNG50 and TNG100, are sufficiently detailed to allow the formation of jellyfish galaxies.

In order to study those simulated jellyfish galaxies, the researchers need to identify them among the tens of thousands of galaxies in their virtual universe. This assessment requires a process that is still tricky for

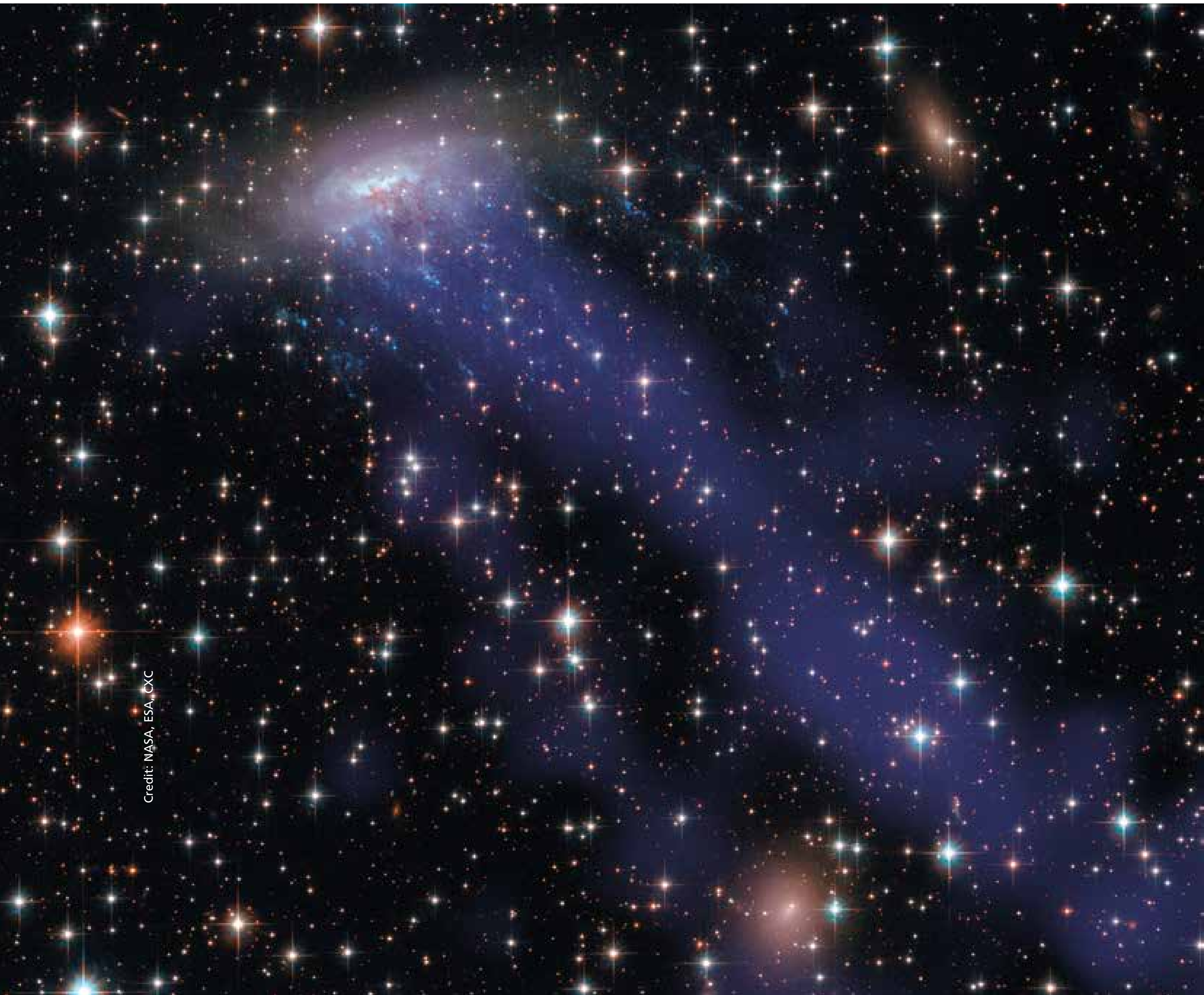


Fig. III.4.2: This image shows the jellyfish galaxy ESO 137-001. Along the electric blue ram pressure stripes emanating from the galaxy, a huge gas stream extends towards the lower edge of the image, visible only in the X-ray region of the spectrum. As well as the electric blue ram pressure stripping streaks seen emanating from ESO 137-001, a giant gas stream extends towards the bottom of the frame, only visible in the X-ray part of the spectrum.

computers to do independently. While current machine learning techniques are pretty good at classifying and grouping shapes and forms, humans must train the algorithms extensively. Instead, letting many human brains do the work directly using their excellent pattern recognition skills is easier. That is why, as a first step, the researchers set out to learn which of their simulated galaxies look like jellyfish to a human observer, with a body made of stars trailing a tail made of gas.

Crowdsourcing jellyfish-galaxy identification

In a pilot study led by Kiyun Yun, one of the group's PhD students, the team members themselves identified 800 jellyfish galaxies among 2600 pre-selected candidates by eye. Nevertheless, that is only a fraction of the available data – and looking at all the data in this fashion is more than a small team of scientists can handle.

At this point, the Zooniverse comes in: the world's largest and most popular platform for people-powered research, specializing in precisely this kind of citizen science. It hosts projects where human volunteers and their pattern-recognition-savvy brains can contribute to cutting-edge scientific research. Parsing through tens of thousands of images in search of rare galaxies is a considerable task but not that difficult if thousands of volunteers take it on.

Building on work by Yun and another group member Elad Zinger, now at the Hebrew University of Jerusalem, post-doctoral researcher Gandhali Joshi transformed the problem of jellyfish galaxy identification into the Zooniverse project "Cosmological Jellyfish".

Kickstarting jellyfish galaxy research

In the project, participants studied pictures, each showing a galaxy in the middle of the image. Each picture showed a particular galaxy from the TNG50 and TNG100 simulations viewed from a random angle. Participants then decided: Does that particular galaxy look like a jellyfish or not?

While the project provided a tutorial and classification feedback for some of the images, nature is messy – even faithfully simulated nature. There will always be cases where it is difficult to decide whether or not a specific galaxy resembles a jellyfish. In the end, it is acceptable to be uncertain: At least twenty different participants classified each galaxy during the project. Eventually, researchers will be able to distinguish galaxies that definitely are, or are not, jellyfish galaxies from more ambiguous specimens (where some participants saw jellyfish, others not).

Once identified, the researchers know which galaxies they will need to look at more closely in their simulated universe. The simulation provides the complete formation history for each galaxy, so at that stage, the scientists should be able to find out how these galaxies formed, how they evolved to look like jellyfish in the first place – and what went differently for the galaxies that do not look like jellyfish.

The Cosmological Jellyfish project on Zooniverse has attracted about 4500 volunteers who have collectively classified more than 80 000 images from the simulations over two periods of just a few weeks in the course of 2021.

Annalisa Pillepich, Gandhali Joshi
(now at University College London, UK), and
Elad Zinger (now at Hebrew University, Jerusalem, Israel)

The Cosmological Jellyfish project is available in English, German, Hebrew, and Italian at:
https://www.zooniverse.org/projects/apillepich/cosmological-jellyfish

III.5 Highlights

When black holes clear the way for star formation in satellite galaxies

Research combining systematic observations with cosmological simulations has found that black holes can suppress mechanisms that impede star formation in galaxies. Astronomers had previously regarded supermassive black holes as a destructive force for star formation on galactic scales. Active black holes can blow away the gas galaxies need to form new stars. The latest results, published in the journal Nature, showcase situations where active black holes can, instead, "clear the way" for galaxies that orbit inside galaxy groups or clusters. It prevents those galaxies from disrupting their star formation as they fly through the surrounding intergalactic gas.

Active black holes are primarily thought to have a destructive influence on their environment. As they blast energy into their host galaxy, they heat and eject that galaxy's gas, making it more difficult for the galaxy to produce new stars. But now, researchers have found that the same activity can, in fact, help with star formation – at least for the satellite galaxies that orbit the host galaxy.

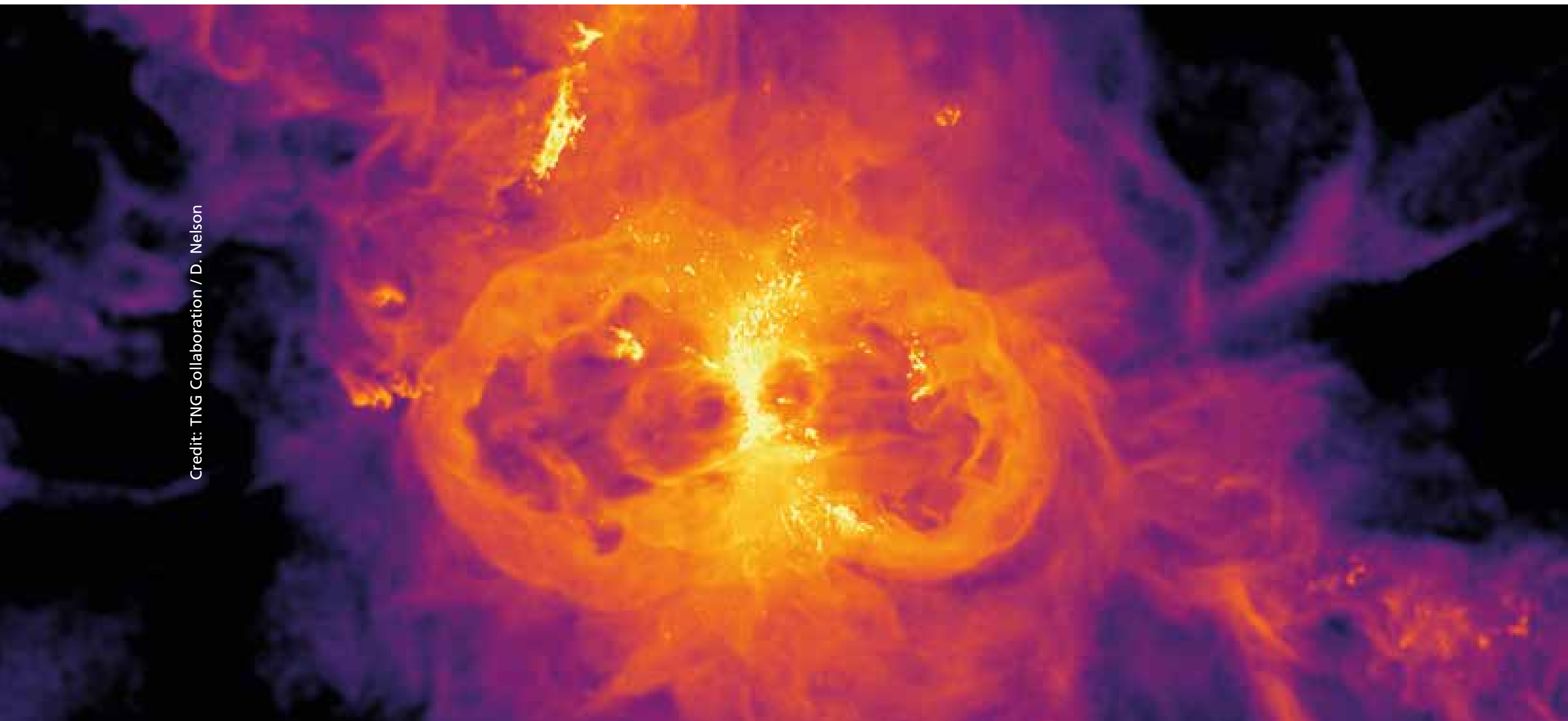
Fig. III.5.1: Gas density around a massive central galaxy in a group in the virtual universe of the TNG50 simulation. Gas inside the galaxy corresponds to the bright vertical structure: a gaseous disk. To the left and right of that structure are bubbles – regions that look like circles in this image, with reduced gas density inside. This geometry of the gas is due to the action of the supermassive black hole that hides at the center of the galaxy, pushing out gas preferably in directions perpendicular to the galaxy's gaseous disk, carving regions of lower density.

The counter-intuitive result came from a collaboration sparked by a lunchtime conversation between astronomers specializing in large-scale computer simulations and those who are experts in observations. It is a good example of the kind of informal interaction that has become more difficult under pandemic conditions.

Star formation in galaxies

Astronomical observations that include taking a distant galaxy's spectrum allow for fairly direct measurements of the rate at which that galaxy is forming new stars. Going by such measurements, some galaxies form stars at relatively sedate rates. In our Milky Way galaxy, only one or two new stars are born each year. Others undergo brief surges of excessive star formation activity, called "starbursts", with hundreds of stars born per year. Star formation appears to be suppressed in yet other galaxies, or "quenched," as astronomers say: Such galaxies have virtually stopped forming new stars.

A special kind of galaxy, specimens of which are frequently – almost half of the time – found to be in such a quenched state, are so-called satellite galaxies. They are part of a group or cluster of galaxies. Their masses are comparatively low, and they orbit a much more massive central galaxy. Such galaxies typically form very few new stars, if at all. Since the 1970s, astronomers have suspected that something akin to headwind might be to blame: Groups and clusters of galaxies contain not only galaxies but also hot thin gas filling the intergalactic space.



Satellite galaxies losing their gas to the headwind effect

As a satellite galaxy orbits through the cluster at a speed of hundreds of kilometers per second, the thin gas lets a satellite encounter the same kind of "headwind" that someone riding a fast bike or a motorbike feels. The satellite galaxy's stars are much too compact to be affected by the steady stream of intergalactic gas.

But the satellite galaxy's gas is not: The oncoming hot gas strips it away in a process known as "ram pressure stripping". On the other hand, a fast-moving galaxy cannot pull in a sufficient amount of intergalactic gas to replenish its gas reservoir. The upshot is that such satellite galaxies lose their gas almost completely and with it the raw material needed for star formation. As a result, the star-formation activity would be quenched.

The use of virtual universes

The processes in question occur over millions or even billions of years, preventing us from watching them directly. But even so, there are ways for astronomers to learn more. They can utilize computer simulations of virtual universes programmed so as to follow the relevant laws of physics and compare the results with what we actually observe. And they can look for tell-tale clues in the comprehensive "snapshot" of cosmic evolution that astronomical observations provide.

Annalisa Pillepich, a group leader at the Max Planck Institute for Astronomy (MPIA), specializes in simulations of this kind. The IllustrisTNG suite of simulations, which Pillepich has co-led, provides the most detailed virtual universes to date – universes in which researchers can follow the movement of gas around on comparatively small scales.

Jellyfish galaxies and simulated black holes with bubbles

IllustrisTNG provides some extreme examples of satellite galaxies freshly stripped by ram pressure: so-called "jellyfish galaxies", which trail the remnants of their gas like jellyfish are trailing their tentacles. But, while jellyfish galaxies are relevant, they are not where the current research project started. In November 2019, Pillepich recounted a different one of her IllustrisTNG results to Ignacio Martín-Navarro, an astronomer specializing in observations, who was at MPIA on a Marie Curie fellowship. They discussed a result of the influence of supermassive black holes that reached beyond the host galaxy and into intergalactic space.

Matter falling onto such a black hole typically becomes part of a rotating so-called accretion disk surrounding it before falling into the black hole itself. This impact onto the accretion disk liberates an enormous amount of energy in the form of radiation and frequently also in the form of two jets. They consist of quickly moving particles, which accelerate away from the black hole at right angles to the accretion disk. A supermassive black hole emitting energy in this way is called an Active Galactic Nucleus, AGN for short.

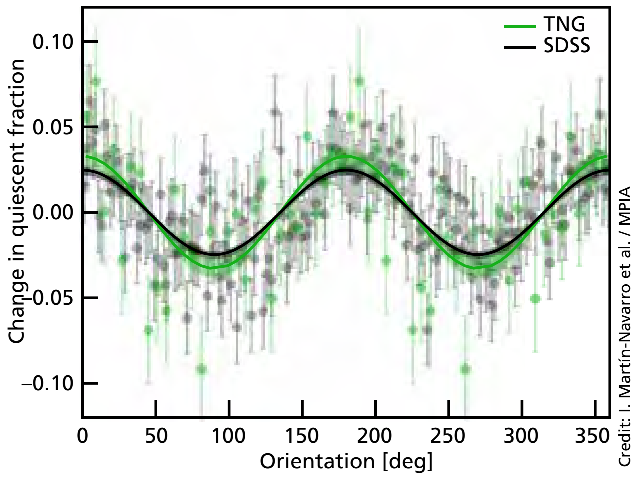


Fig. III.5.2: Illustration of the change of fraction of quiescent galaxies observed in SDSS and calculated from the TNG simulation. The fraction of quiescent galaxies depends on their orientation to the central galaxy's major axis. Quiescent galaxies are relatively enhanced along the direction of the major axis and, conversely, relatively deficient in the direction of the minor axis.

While IllustrisTNG is not detailed enough to include black hole jets, it does contain physical terms that simulate how an AGN injects energy into the surrounding gas. As the simulation showed, such an energy transfer leads to gas outflows, which orient themselves along a path of least resistance. In the case of disk galaxies similar to our Milky Way, they align perpendicular to the stellar disk; for so-called elliptical galaxies, perpendicular to a suitable preferred plane defined by the arrangement of the galaxy's stars.

Over time, the bipolar gas outflows will affect the intergalactic environment – the thin gas surrounding the galaxy. They will push the intergalactic gas away, each outflow creating a gigantic bubble. If a satellite galaxy were to pass through that bubble – would it be affected by the outflow, and would its star formation activity become quenched even further?

An observable difference

Martín-Navarro found some clues to answering that question by examining 30 000 galaxy groups and clusters in the 10th data release of the Sloan Digital Sky Survey (SDSS), which provides high-quality images of a large part of the Northern hemisphere. Each of those galaxy clusters contains a central galaxy and, on average, four satellite galaxies.

In a statistical analysis of those thousands of systems, he found a small difference between satellite galaxies close to the central galaxy's preferred plane and satellites markedly above and below. But the difference was in the opposite direction the researchers had expected: Satellites above and below the plane, within the thinner bubbles, were, on average, about 5% less likely to have had their star formation activity quenched.

Confirmation in a virtual universe

Inspired by that surprising result, Martín-Navarro and Annalisa Pillepich performed the same statistical analysis in the virtual universe of the IllustrisTNG simulations. After all, in simulations of that kind, researchers do not put in cosmic evolution "by hand". Instead, the software includes algorithms that model the laws of physics for that virtual universe as naturally as possible, with suitable initial conditions corresponding to our universe's state shortly after the Big Bang.

That is why simulations like that leave room for the unexpected – in this case, for re-discovering the on-plane, off-plane distribution of quenched satellite galaxies: The virtual universe showed the same 5% deviation for the quenching of satellite galaxies! Evidently, the researchers were on to something.

How black holes can facilitate star formation

In time, the team devised a hypothesis for the physical mechanism behind the quenching variation. Consider a satellite galaxy traveling through one of the thinned-out bubbles the central black hole has blown into the surrounding intergalactic medium. Due to the lower density, that satellite galaxy experiences less headwind and ram pressure and is thus less likely to have its gas stripped away.

Then, it is down to statistics. The effect will not be noticeable for satellite galaxies that have orbited the same central galaxies several times already, traversing bubbles and the higher-density regions in between. Such galaxies will have lost their gas long ago. But for satellite galaxies that have recently joined the group or cluster, location will make a difference: If those satellites happen to land in a bubble first, they are less likely to lose their gas than if they happen to land outside a bubble. This effect could account for the statistical difference for the quenched satellite galaxies.

Following up on the quenched satellites

The excellent agreement between the statistical analyses of the SDSS observations and the IllustrisTNG simulations supported by a plausible hypothesis for a mechanism is an encouraging result. It is particularly interesting in the context of galaxy evolution because it indirectly confirms the role of active galactic nuclei in heating intergalactic gas and actively "pushing it away" to create lower-density regions.

As with all promising results, there are now several natural directions that either Martín-Navarro, Pillepich, and their colleagues or other scientists can take to explore further. First, there are additional simulations with the same scope as IllustrisTNG but which model cosmic evolution somewhat differently. Do those simulations, such as the EAGLE simulation, yield the same results?

The distant past and a space telescope in the present

Also, the SDSS observations show the Universe at a comparatively recent time. As astronomers look deeper into space, they see objects as they were long ago. If we look at the Andromeda galaxy, we see that galaxy as it was 2.5 million years ago – simply because the galaxy's light has taken 2.5 million years to reach us. This circumstance allows astronomers to observe the distant past of distant regions directly.

That raises the question: Will observations that systematically target much more distant galaxies than SDSS, aiming at the early universe (higher redshifts), show the same statistical phenomenon for those ancient satellite galaxies? From the proposed mechanism, one would expect the statistical effect to have been more pronounced in the past – and that is a testable prediction to be investigated in both observations and simulations of cosmic evolution.

Annalisa Pillepich, Ignacio Martín-Navarro (now Instituto de Astrofisica de Canarias, Tenerife, Spain), Martina Donnari

Ignacio Martín-Navarro, Annalisa Pillepich, Dylan Nelson et al., "Anisotropic satellite galaxy quenching modulated by black hole activity" in Nature, Vol. 594, 187 (2021). DOI: 10.1038/s41586-021-03545-9

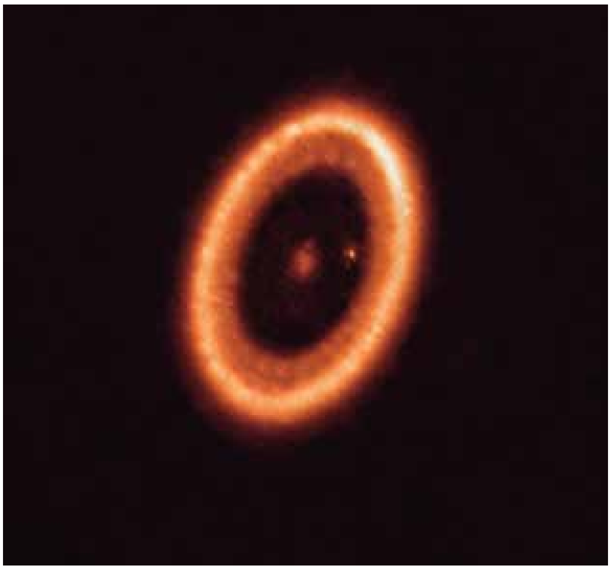
III.6 Highlights

First clear detection of a moon-forming disk around an exoplanet

An international group of researchers have, for the first time, unambiguously detected a disk of dust around a planet outside our solar system. The team observed the exoplanet system of PDS 70, which is 400 light-years away, with the Atacama Large Millimetre/Submillimetre Array (ALMA). The circumplanetary disk of the giant gas planet PDS 70c contains enough material to produce up to three satellites the size of the Moon. These results will provide new insights into how moons and planets form in young planetary systems.

The formation of the Earth's moon has been a constant subject of scientific debate and is still not fully understood today. Even more so, astronomers are keen to study the formation of natural satellites around distant exoplanets to reveal their formation mechanisms. With the study presented here, Miriam Keppler and other scientists have unequivocally identified a disk around a Jupiter-like exoplanet that bears the potential to produce moons.

Fig. III.6.1: This image, taken with the Atacama Large Millimeter/submillimeter Array (ALMA), shows the distribution of dust in the PDS 70 planetary system, which predominantly forms a ring. The system contains the moon-forming disk visible as a bright dot at the inner rim of the ring surrounding PDS 70c, a young Jupiter-like planet nearly 400 light-years away. The star PDS 70 at the center of the dust ring is invisible at the observed wavelengths. Instead, it hosts an unresolved inner dust disk.



Credit: ALMA (ESO / NAOJ / NRAO) / Benisty et al.

The disk in question, called a circumplanetary disk, surrounds the exoplanet PDS 70c. It is one of two giant, Jupiter-like planets orbiting the star PDS 70, nearly 400 light-years away. Astronomers had found hints of a "moon-forming" disk around this exoplanet before, but since they failed to tell the disk apart from its surrounding environment, they could not confirm its detection — until now.

A few years earlier, Keppler had found the first planet orbiting this star. Therefore, the two planets revolve around their star at distances similar to where Uranus and Neptune orbit the Sun.

The team also found the disk to have the same diameter as the Earth's orbit around the Sun. It comprises enough mass to form up to three satellites the size of the Moon. However, the results are not only key to finding out how moons emerge. These new observations are also essential to prove theories of planet formation that have escaped testing so far.

The results follow from observations obtained with the Atacama Large Millimetre/Submillimetre Array (ALMA) located in the Atacama Desert in Chile. At the distance of the PDS 70 system, the excellent angular resolution of approximately 20 milliarcseconds corresponds to a spatial extent of roughly 2.3 au. The ability to probe the planetary system in such detail allowed the researchers to determine the disk's association with the planet and constrain its size for the first time.

Planets form in dusty disks around young stars, carving out cavities as they collect material from this circumstellar disk to grow. In this process, a planet can acquire its own circumplanetary disk, contributing to the planet's growth by regulating the amount of material falling onto it. In the case of PDS 70c, the accretion rate is 10^{-8} Jovian masses per year. At the same time, the gas and dust in the circumplanetary disk can condense into progressively larger bodies through multiple collisions, ultimately leading to the birth of moons.

Nevertheless, astronomers do not yet fully understand the details of these processes. It is still unclear when, where, and how planets and moons form. The more than 4000 exoplanets discovered to date populate mature systems. PDS 70b and PDS 70c, which form a system reminiscent of the Jupiter-Saturn duo, are the only two exoplanets detected so far that are still in their stage of formation. They were first discovered in 2018 and 2019, respectively. Their unique nature prompted repeated observations with other telescopes and instruments.

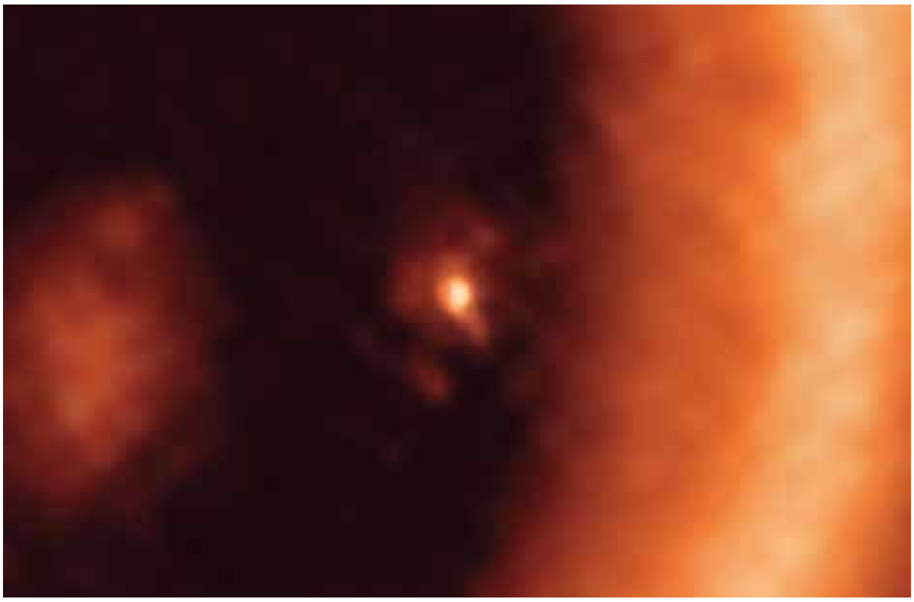


Fig. III.6.2: This image, taken with the Atacama Large Millimeter/submillimeter Array (ALMA), shows a close-up view of the moon-forming disk surrounding PDS 70c, a young Jupiter-like gas giant nearly 400 light-years away. The planet itself is invisible at these wavelengths. It resides near the inner rim of the larger circumstellar ring-like disk, taking up most of the right-hand side of the image. The dusty circumplanetary disk is as large as the Earth's orbit around the Sun and contains enough mass to form up to three satellites the size of the Moon.

The latest high-resolution ALMA observations have allowed astronomers to gain further insights into the system. In addition to confirming the detection of the circumplanetary disk around PDS 70c and studying its size and mass, they found that PDS 70b does not show clear evidence of such a disk. This result indicates PDS 70c deprived it of dust material in its natal environment.

In the last two decades, we have discovered planet-forming disks around young stars. Now, we are taking on the new challenge of studying the disks around young planets. The ALMA observations of circumplanetary disks are a big step in this direction.

Miriam Keppler, Nicolas T. Kurtovic, Paola Pinilla and Thomas Henning

in collaboration with
Myriam Benisty (Unidad Mixta Internacional Franco-Chilena de Astronomía, Universidad de Chile, Santiago de Chile, Chile and Université Grenoble Alpes, France), Jaehan Bae (University of Florida, Gainesville, USA), Stefano Facchini (Università degli Studi di Milano, Italy), Richard Teague (Harvard-Smithsonian Center for Astrophysics, Cambridge, USA)

Myriam Benisty, Jaehan Bae, Stefano Facchini, Miriam Keppler et al., "A Circumplanetary Disk around PDS70c" in The Astrophysical Journal Letters, 916, L2 (2021). DOI: 10.3847/2041-8213/ac0f83

III.7 Highlights

How to weigh a quasar

Astronomers have successfully tested a new method for determining the masses of extreme black holes in quasars for the first time. This method is called spectroastrometry and uses the measurement of radiation emitted by gas in the vicinity of supermassive black holes. Spectroastrometry is relatively straightforward and efficient compared to other methods if performed with large modern telescopes. The high sensitivity of this method permits investigating the surroundings of luminous quasars and supermassive black holes in the early universe.

In cosmology, determining the mass of supermassive black holes in the young universe is an essential measurement for tracking the temporal evolution of the cosmos. Patzer prize winner Felix Bosco, in close collaboration with Jörg-Uwe Pott and former MPIA researchers Jonathan Stern and Joseph Hennawi, has successfully demonstrated the feasibility of directly determining the mass of a quasar using spectroastrometry.

This method allows the mass of distant black holes in luminous quasars to be determined directly from optical spectra without requiring extensive assumptions about the spatial distribution of gas. The spectacular applications of spectroastrometric measurements of quasar masses were systematically investigated at MPIA several years ago.

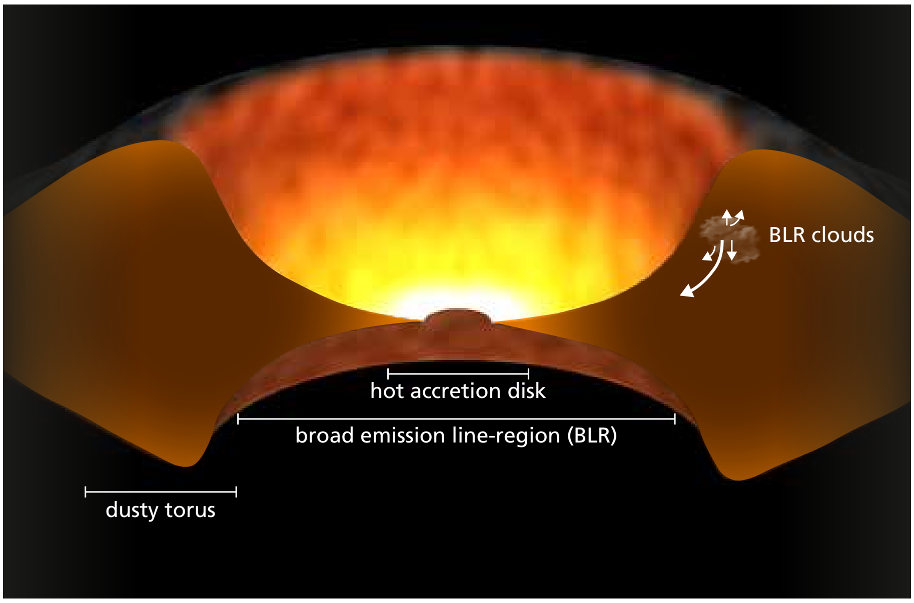
Quasars: beacons of the Universe

Quasars contain supermassive black holes in the centers of galaxies and are among the brightest cosmic objects. Therefore, they are detectable over large distances and thus enable the exploration of the early universe.

If there is gas near a black hole, it cannot fall into it directly. Instead, an accretion disk forms, a vortex that helps regulate the matter flow into the black hole. High frictional forces in this gas stream, which ultimately feeds the black hole, typically heat the accretion disk to fifty thousand degrees. The intensity of the radiation emitted in the process makes the quasars appear so bright that they outshine all the stars in the galaxy.

Other components within quasars have been known for several decades, such as the so-called "broad emission-line region" (BLR), a zone in which ionized gas clouds orbit the central black hole at several thousand

Fig. III.7.1: Schematic representation of a quasar. The hot accretion disk in the center surrounds the black hole, which is invisible here. A dense distribution of gas and dust surrounds it in which individual ionized gas clouds orbit the black hole at high speeds. Stimulated by the intense and high-energy radiation of the accretion disk, these clouds emit radiation in the form of spectral lines, broadened due to the Doppler effect. Therefore, the zone of these gas clouds is called the broad emission-line region (BLR).



Credit: Bosco / MPIA, MPIA graphics department

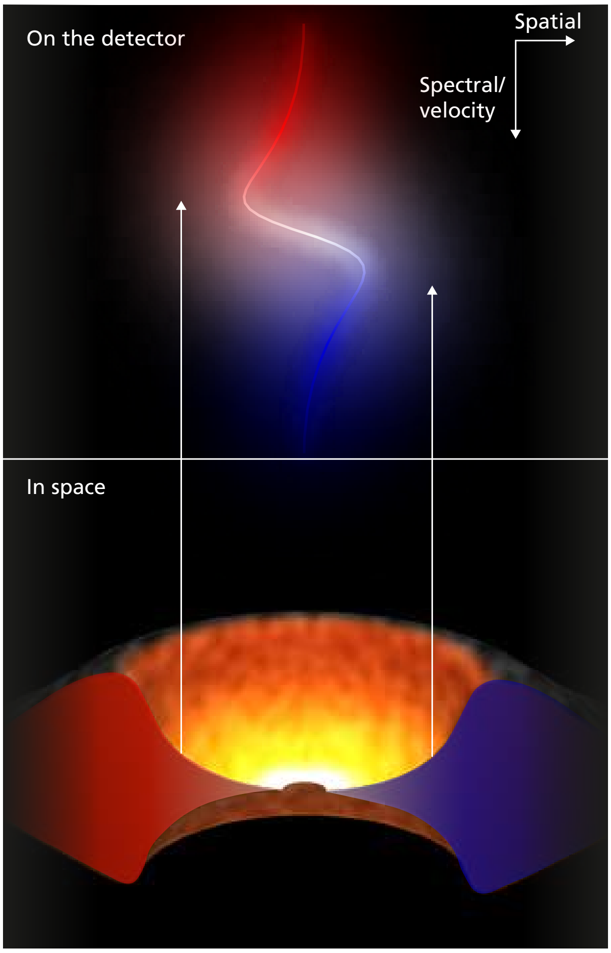


Fig. III.7.2: Schematic representation of the origin of the spectroastrometry signal. If the ionized gas were at rest, we would measure the same wavelength of the spectral line throughout the BLR. However, the gas clouds orbit the black hole. Seen from the side, they come towards us on one side while moving away again on the other. As a result, the spectral signal appears blue-shifted towards shorter wavelengths on one side. On the other side, it is red-shifted towards longer wavelengths. As indicated above, the measured wavelength variations across the BLR result in the spectroastrometry signal. From this, researchers can determine the maximum distance of the observed BLR clouds from the quasar's center and the prevailing velocity there.

kilometers per second. The intense and energetic radiation from the accretion disk stimulates emission from the gas in the BLR, which is visible in the spectra in the form of spectral lines. However, due to the Doppler effect, they are strongly broadened by the high orbital velocities, thus giving the BLR its name.

A new method of measuring black hole masses

Felix Bosco and his colleagues have measured the optically brightest spectral line of hydrogen (Hα) in the BLR of the quasar J2123-0050 in the constellation Aquarius. Its light stems from a time when the Universe was just 2.9 billion years old. Using the method of spectroastrometry, they have determined the putative distance of the radiation source in the BLR to the center of the accretion disk, where they suspect a supermassive black hole. At the same time, the Hα line provides the radial velocity of the hydrogen gas, i.e., that velocity component that points towards Earth. The mass of the central black hole can be precisely deduced from this data if the gas distribution can be spatially resolved. The underlying physics is very similar to the Solar System, where the Sun's mass determines the planetary motions.

Unfortunately, even for today's large telescopes, the extent of the BLR is far too small for this. However, by separating spectral and spatial information in the collected light and statistically modeling the measured data, astronomers can derive distances of much less than one image pixel from the center of the accretion disk. The duration of the observations determines the precision of the measurement.

By observing J2123-0050, the team's main goal was to show the spectroastrometry method's ability to detect the kinematic signature of the central quasar masses using the 8-meter-class telescopes already available today. Moreover, although deriving the black hole mass was only a secondary objective, they managed to calculate an upper limit of 1.8 billion solar masses.

This result proves that spectroastrometry could be a valuable addition to the tools researchers use to determine black hole masses. By employing much more sensitive next-generation telescopes like the James Webb Space Telescope (JWST) and the Extremely Large Telescope (ELT with a primary mirror diameter of 39 meters), astronomers will soon be able to determine quasar masses at the highest redshifts. The current feasibility study helps define and prepare already planned ELT research programs.

Spectroastrometry – a valuable addition to classical methods

Among the alternatives for surveying BLR in nearby quasars is a widely used method: "Reverberation Mapping" (RM). It employs the light transit time any brightness fluctuation in the accretion disk needs to excite the surrounding gas to increased radiation. From this, astronomers estimate the mean extent of the BLR. Besides the sometimes large uncertainties in the assumptions, this method has considerable disadvantages compared to spectroastrometry when investigating the most massive and distant black holes. The BLR diameter correlates with the mass of the central black hole. Hence, the signal delay between the accretion disk and the BLR becomes very large for massive black holes in the early universe. The necessary series of measurements of several years become impractically long.

Fig. III.7.3: Photo of the dome of the Gemini North telescope in Hawaii, USA. This telescope has a primary mirror diameter of 8.1 meters and a laser guide star that, together with adaptive optics, helps minimize the influence of the atmosphere on observations. Gemini North was used for the spectroastrometry feasibility study.

Moreover, the brightness fluctuations and their ability to measure them tend to decrease for large black hole masses and quasar luminosities. The RM method is, therefore, rarely applicable to luminous quasars. As a result, it is not suitable for measuring quasars at large cosmological distances.

However, the RM serves as a basis for calibrating other indirect methods first established for nearby quasars and then extended to more distant, luminous quasars with massive black holes. The quality of these indirect approaches stands and falls with the accuracy of the RM method. Here, too, spectroastrometry can help put the mass determination of massive black holes on a broader basis. For example, evaluating the data from J2123-0050 indicates that the correlation between the BLR size and the quasar luminosity, initially established with the RM method for relatively close and faint quasars, seems to hold for luminous quasars as well. However, further measurements are needed here.

The BLR can also be measured interferometrically in nearby active galaxies, such as with the GRAVITY instrument of the Very Large Telescope Interferometer (VLTI). However, the great advantage of spectroastrometry is that only a single highly-sensitive observation is needed. In addition, it works without the technically very complex coupling of several telescopes as required by interferometry nor long series of measurements over months and years, as is the case with the RM. For example, a single series of observations with an exposure time of four hours with the 8-meter-class Gemini North telescope in Hawaii, supported by a correction system consisting of a laser guide star and adaptive optics, was sufficient for the research group led by Felix Bosco.

Opening a new door to the exploration of the early universe

Researchers have high hopes for the next generation of large optical telescopes such as ESO's ELT. Combining an enlarged light-collecting surface with fivefold increased image sharpness would make the observation presented here possible in just a few minutes at the ELT. The authors already plan to use the ELT to measure numerous quasars at different distances astrometrically. A single night would suffice to observe the cosmological evolution of black hole masses directly. With the successful astrometric feasibility study, the authors have pushed wide open a new door to exploring the early universe.

Felix Bosco (left MPIA and academia) and Jörg-Uwe Pott

in collaboration with
Joseph F. Hennawi (UC Santa Barbara, USA and Leiden University, The Netherlands),
Jonathan Stern (Tel Aviv University, Israel)

Felix Bosco, Joseph F. Hennawi, Jonathan Stern and Jörg-Uwe Pott, "Spatially Resolving the Kinematics of the ≲100 µas Quasar Broad-line Region Using Spectroastrometry. II. The First Tentative Detection in a Luminous Quasar at *z* = 2.3" in The Astrophysical Journal, Vol. 919, 31 (2021). DOI: 10.3847/1538-4357/ac106a

Jonathan Stern, Joseph F. Hennawi and Jörg-Uwe Pott, "Spatially Resolving the Kinematics of the ≲100 µas Quasar Broad-line Region Using Spectroastrometry" in The Astrophysical Journal, Vol. 804, 1 (2015). DOI: 10.1088/0004-637X/804/1/57

III.8 Highlights

A gigantic lane made of raw material for new stars

Astronomers have identified one of the longest known structures in the Milky Way. It stretches some 3900 light-years and consists almost entirely of atomic hydrogen gas. This filament, called "Maggie", could represent a link in the matter cycle of the stars. Analyzing the measurements suggests that the atomic gas in this lane converges locally to form molecular hydrogen. When compressed in large clouds, this is the material from which stars eventually form.

Hydrogen is the most widespread substance in the Universe and the main ingredient in the formation of stars. Unfortunately, detecting individual clouds of hydrogen gas is a demanding task, which makes research into the early phases of star formation challenging. That is why the recent discovery of a surprisingly long structure, a filament, of atomic hydrogen gas is even more exciting.

The filament's convenient location helped the astronomer Jonas Syed to find it. About 1600 light-years below and running parallel to the galactic plane, it prominently stands out against the background of the ambient gas when looking at the 21-centimeter spectral line emitted by atomic hydrogen. Since the emission consists of a single spectral line, any shift in the observed wavelength reveals the velocity of the hydrogen gas. Analyzing those velocities allowed Syed and his colleagues to show that they barely differ along the filament. Therefore, the researchers conclude that it is indeed a coherent structure.

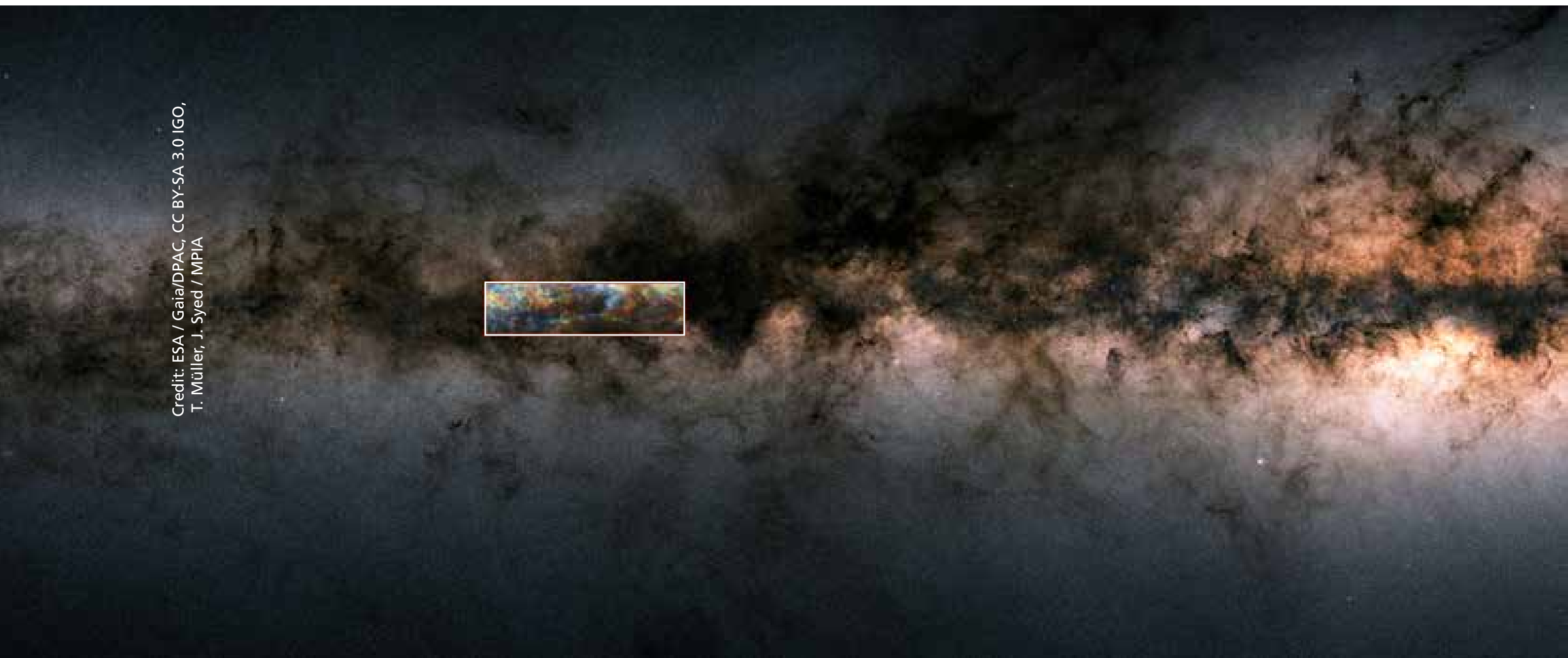
Its mean velocity is determined mainly by the rotation of the Milky Way disk. Combining this information with a new method for analyzing the data, the collaborating astronomer Sümeyye Suri measured the filament's size and distance. It is about 3900 light-years long and 130 light-years wide. At a distance of around 55 000 light-years, it is on the far side of the Milky Way. In contrast, the largest known clouds of molecular gas typically extend "only" about 800 light-years across.

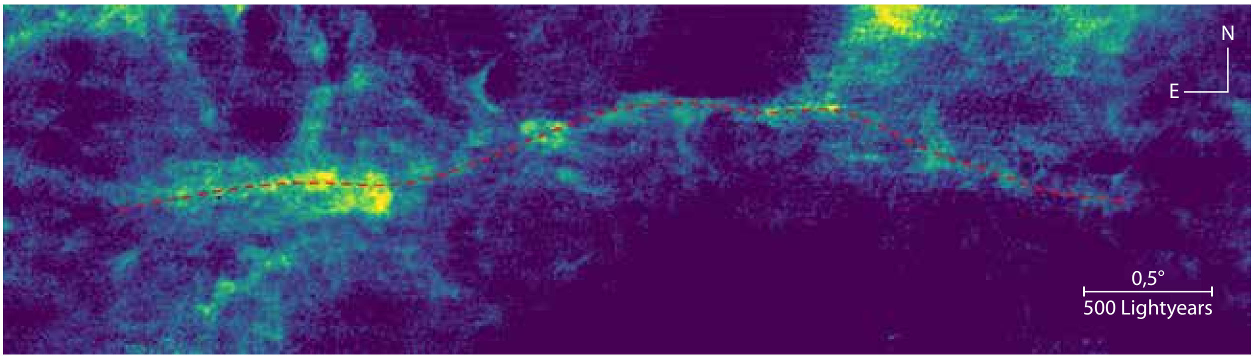
The data stem from the MPIA-led THOR (The HI/OH/Recombination line survey of the Milky Way) observing program. This survey collects radio data of the Milky Way accessible from the Very Large Array (VLA) in the spectral lines of atomic hydrogen, the hydroxyl molecule (OH), 19 H alpha transitions, and the spectral continuum from 1 to 2 GHz at an angular resolution of about 20 arcseconds.

Hydrogen occurs in the Universe in various states. Astronomers find it in the form of atoms and molecules, in which two atoms are joined together. Only molecular gas condenses to relatively compact clouds, which develop frosty regions where new stars finally emerge. But exactly how the transition from atomic to molecular hydrogen happens is still largely unknown. That makes the opportunity to study this extraordinarily long filament all the more exciting.

Fellow astronomer Juan D. Soler found the first clue to this object a year earlier. He named this filament "Maggie" after the longest river in his home country

Fig. III.8.1: This image shows a section of the side view of the Milky Way as measured by ESA's Gaia satellite. The dark band consists of gas and dust, which dims the light from the embedded stars. The Galactic Centre of the Milky Way is indicated on the right of the image, shining brightly below the dark zone. The box to the left of the middle marks the location of the "Maggie" filament. It shows the distribution of atomic hydrogen. The colors denote different gas velocities.





Credit: J. Syed / MPIA

Fig. III.8.2: This false-color image shows the distribution of atomic hydrogen measured at a wavelength of 21 cm. The red dashed line traces the "Maggie" filament.

of Colombia, called the Río Magdalena. It was already recognizable in earlier evaluations of the data, but only the current study proves that it is a coherent structure.

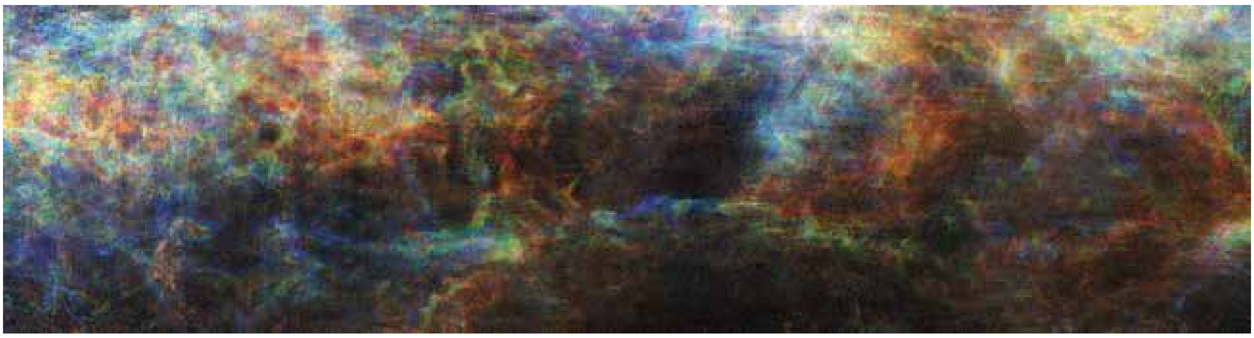
On closer inspection, the team noticed that the gas converges at some points along the filament. They conclude that the hydrogen gas accumulates at those locations and condenses into large clouds. The researchers also suspect those are the environments where the atomic gas gradually changes into its molecular form.

In previously published data, they indeed found evidence of Maggie containing molecular hydrogen at a mass fraction of about 8%. We may be looking at a region in the Milky Way where the immediate raw material for new stars is being produced. Hence, new stars could form here in the distant future. However, many questions still remain unanswered. The astronomers have gathered additional data, which they hope will provide more clues about the fraction of molecular gas.

Jonas Syed, Juan D. Soler (now: Instituto Nazionale di Astrofisica, Rome, Italy), Henrik Beuther, Yuan Wang, Sümeyye Suri (now: Universität Wien, Austria), Jonathan D. Henshaw, Manuel Riener, Sara Rezaei Khoshbakht (also: Chalmers tekniska högskola, Gothenburg, Sweden), Hendrik Linz

in collaboration with
Shmuel Bialy (University of Maryland, USA), Rowan J. Smith (Jodrell Bank Centre for Astrophysics, University of Manchester, UK), Jeroen M. Stil (The University of Calgary, Canada)

Fig. III.8.3: This image corresponds to the box in Fig. III.8.1. In addition to the distribution of atomic hydrogen, the colors indicate different gas velocity ranges as measured by the observations of the THOR survey. The "Maggie" filament is visible in the lower area.



Credit: T. Müller, J. Syed / MPIA

J. Syed, J. D. Soler, H. Beuther et al., "The "Maggie" filament: Physical properties of a giant atomic cloud" in Astronomy & Astrophysics, 657, A1 (2022). DOI: 10.1051/0004-6361/202141265

IV. Instrumentation and Technology

Credit: C. Gunn / NASA

IV.1 Overview

Instrumentation for Ground-based Astronomy

In 2021, MPIA activities in the area of ground-based instrumentation regained momentum after having been slowed down by the pandemic in the previous year. As it was not yet possible to continue the commissioning work for a high-resolution imager for the Large Binocular Telescope (LBT), the MPIA technical departments continued to concentrate on spectroscopy and high fidelity imaging for the future Extremely Large Telescope (ELT) of the European Southern Observatory (ESO), on multi-object spectroscopy for ESO's VISTA telescope, survey instrumentation for Calar Alto, on our contribution to a new imaging and spectroscopy instrument for the 2.5-meter Nordic Optical Telescope on La Palma, and on the development of four telescope systems to be located at Las Campanas Observatory in Chile. To keep up with the latest developments in infrared detectors, MPIA also continued working on a project to adapt our in-house read-out electronics to a novel type of detector. MPIA's principal instrumentation projects consist of building two of the three first-light instruments for the ELT, a next generation telescope with a main mirror 39 meters in diameter.

Instrumentation for the Large Binocular Telescope (LBT)

The largest ongoing MPIA instrumentation project up to now has been the near-infrared high-resolution imager LINC-NIRVANA (L-N). This instrument was finally installed at the LBT on Mt. Graham, Arizona, in late September 2016. It saw nine separate commissioning runs up to 2019, and one in February 2020. Three or four more were to come, but were suspended because of the pandemic situation both in Europe and the USA. MPIA is the lead institute in the L-N consortium, which also includes Italian Observatories (INAF), the Max Planck Institute for Radio Astronomy in Bonn, and the University of Cologne.

Fig. IV.1.1: Bird's eye view of Cerro Paranal with ESO's Very Large Telescope (VLT) and – in the back – the 4.1-meter VISTA telescope where the new instrument 4MOST is planned to be installed in summer 2023.

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

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

Credit: D. Juncher and the Nordic Optical Telescope

Fig. IV.1.2: The 2.5-meter Nordic Optical Telescope on Roque de los Muchachos Observatory on La Palma, Canary Islands, during nighttime observations. It will host the NTE instrument.

Instrumentation for ESO's VISTA telescope

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

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

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

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

CARMENES is a pair of high-resolution Échelle Spectrographs at the CAHA 3.5-meter telescope, operating, respectively, at visual and infrared wavelengths. It was built by a consortium of five German and six Spanish institutions. With originally 750 guaranteed observing nights available,

Fig. IV.1.3: Construction of the LVM enclosure at Las Campanas Observatory

Credit: C. S. Froning (U-Texas at Austin)

CARMENES began its radial velocity survey for extrasolar planets in January 2016. This survey targets 300 M-type main-sequence stars in order to find low-mass exoplanets in their habitable zones. The guaranteed time was used up by mid-2020, but the survey received a substantial extension which will keep it running until 2023.

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

Instrumentation for the SDSS V – Local Volume Mapper

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

The future Extremely Large Telescope (ELT)

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

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

METIS is a thermal/mid-infrared imager and spectrograph covering a wavelength range between 3 and 19 micrometers. Adaptive optics will permit the instrument to perform diffraction-limited observations, making full use of the telescope's impressive size. The instrument's science case includes exoplanet detection and characterization, the formation and evolution of protoplanetary

Fig. IV.1.4: A bird's eye view of the construction site of ESO's Extremely Large Telescope on Cerro Armazones, taken in January 2022.

disks and extrasolar planets, conditions in the early Solar System, studies of the Galactic Center and of the luminous centers of nearby galaxies, high-redshift active galactic nuclei and high-redshift gamma ray bursts.

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

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

Technology development at MPIA

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

Martin Kürster for the MPIA Technical Departments

IV.2 Overview

Instrumentation for Space-based Astronomy

Contributing instrumentation to space-based telescopes has been a central part of MPIA's instrumentation work for decades. Memorable highlights include contributions to ESA's Infrared Space Observatory (ISO) and Herschel Space Observatory. Using space telescopes expands the toolset of MPIA researchers, as they open windows to processes in space that are not accessible by observations from the ground. In December 2021, the work of decades finally paid off: with the launch of the James Webb Space Telescope (JWST). On board: technology developed by MPIA. However, the next project is already in progress. MPIA contributes mechanisms for the Coronagraphic Instrument (CGI) of NASA's 2.4-meter Nancy Grace Roman Space Telescope, which is slated for launch in 2027.

Instrumentation for the James Webb Space Telescope (JWST)

On 25 December 2021, after decades of planning, development, and construction, and several delays, the James Webb Space Telescope (JWST) was launched into space on an Ariane 5 rocket from the European spaceport Kourou in French Guiana. MPIA supplied various technical key components for two of the scientific instruments on board. The lead for the institute's technical contributions to JWST is Oliver Krause, head of MPIA's Infrared Space Astronomy group. The contributions built on the decade-long experience that MPIA's technical departments, which include laboratories, a design office and workshops for electronics and precision mechanics, have been able to gain in the area of space-born instrumentation. This expertise was crucial in the development of these sophisticated components for the JWST.

MPIA is one of the leading partners in the European consortium for MIRI, the Mid InfraRed Instrument aboard JWST. MIRI will operate in the infrared region of the spec-

Credit: Stephen Kill, STFC

Fig. IV.2.1: MIRI, the Mid Infrared Instrument, during ambient temperature alignment testing at the Science and Technology Facilities Council's Rutherford Appleton Laboratory, UK. MIRI is the first instrument to be completed for the JWST mission, which is scheduled to launch in 2018.

trum, at wavelengths between five and 28 micrometers. The instrument is so sensitive that it could detect a candle on one of Jupiter's moons. MPIA engineers, supported by Hensoldt AG in Oberkochen, developed, among other parts, a filter wheel for the MIRI camera. This wheel is equipped with 18 optical elements which modify the radiation entering the camera before it reaches the detectors. These elements comprise wavelength selecting filters, coronagraphs, and a prism with a spectral resolving power of R~100 between five and 12 microns.

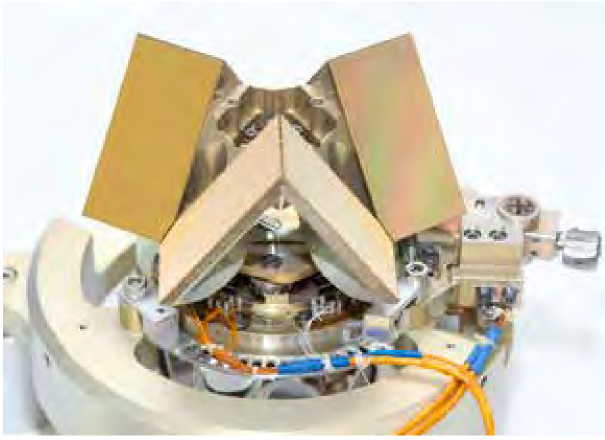
The wheel body rotates around a central axis with specialized bearings. A ratchet system ensures high-precision positioning for each optical element. A brushless (and gearless) central torque motor is used to operate the wheel in an open-loop drive. This requires only relatively simple but robust drive electronics. In addition, this construction minimizes the number of harnesses from the warm electronics to the cryogenic part of the instrument and thus the conducted heat load. The chosen wheel design guarantees high precision and highly reliable positioning of the optical elements while using low driving power, in particular, zero power during science operation, and therefore low heat injection into the cooled MIRI instrument.

MPIA also supplied two grating wheels for the MIRI spectrograph, with a drive design very similar to that of the camera filter wheel. The gratings can be used for mid-infrared spectroscopy within four spectral bands extending between four and 28 microns, with resolving powers between 1330 and 3750. In addition, MPIA is the MIRI consortium lead for the development of the MIRI instrument's electrical system.

MPIA was also involved in developing a filter and a grating wheel for the NIRSpec (Near InfraRed Spectrograph) instrument. NIRSpec covers a spectral range between 0.6 and five micrometers, and offers resolving powers between 100 and 2700 across four observing modes.

Fig. IV.2.2: The filter wheel makes MIRI a scientific instrument. With the exception of the optical elements, the MPIA has planned, designed, built, and tested the filter wheel. The 18 optical elements include filters to narrow the wavelength range, coronagraphs to cover bright objects, and a prism.

Credit: MPIA



Credit: Hensoldt AG

Fig. IV.2.3: The MIRI grating wheel, also referred to as the Dichroic/Grating Assembly (DGA), facilitates spectroscopy of mid-infrared radiation at wavelengths between four and 28 microns.

All these cryo-mechanisms, i.e. moving parts that operate under extreme cold, have to withstand temperatures as low as -266 °C, achieved by additional cooling devices. Conventional materials and lubricants would not work under these conditions. The mechanisms must work precisely, durably, and, above all, maintenance-free. After all, repair flights like those at the beginning of the operation of the Hubble Space Telescope are not possible with the JWST since it does not work in an Earth orbit. Instead, it operates at a distance of 1.5 million kilometers from Earth.

MPIA and its industrial contractors have already delivered their instrumental hardware contributions to NASA in 2012/2013. Since then, the instruments have had to undergo a series of rigorous test campaigns. MPIA's JWST team was instrumental in preparing, conducting, and evaluating these tests at NASA in the USA. In addition, the MPIA team is playing a key role in the development of future data processing software for the MIRI instrument.

In return for their technical contributions, MPIA has received a considerable amount of observing time through a Guaranteed Time (GT) Program: a guaranteed amount of time that MPIA astronomers will be able to observe with JWST without the need for going through the usual application process. That is not to say that MPIA astronomers have not also been very successful in the competitive proposal programme open to all researchers, where only the best programs prevail in a peer-reviewed competition for the limited resource of time. On the contrary, MPIA astronomers have managed to secure an impressively large share of time in this programme, as well. Altogether, MPIA scientists participate in more than 40 open-time observing programs. Eight of them are under the MPIA lead.

As co-investigator of the MIRI instrument, MPIA director Thomas Henning is in charge of one of the major MIRI science projects. Its aim is to find out what build-

Credit: Hensoldt AG

Fig. IV.2.4: The NIRSpec filter wheel preselects the spectral range for near-infrared spectroscopy. It is equipped with 3 long-pass filters, 3 broad-band filters, a CaF_2 plate as a clear aperture, and a shutter/diffuser component.

ing material planets find in their birthplaces, the disks of gas and dust around young stars. In order to do this, his group will use the MIRI spectrograph to elucidate the chemical composition of the gas and dust particles. MPIA director Laura Kreidberg even leads two programs that aim at investigating hot Jupiter exoplanets. Several astronomers have moved from the US to the MPIA to conduct world-leading research with the JWST.

The James Webb Space Telescope has been under development since 1996 under the auspices of NASA. In terms of the findings to be expected, it is regarded as the successor to the Hubble Space Telescope. Hubble has been delivering impressive images and groundbreaking discoveries for more than 30 years. The expectations for the JWST are correspondingly high.

Instrumentation for the Nancy Grace Roman Space Telescope

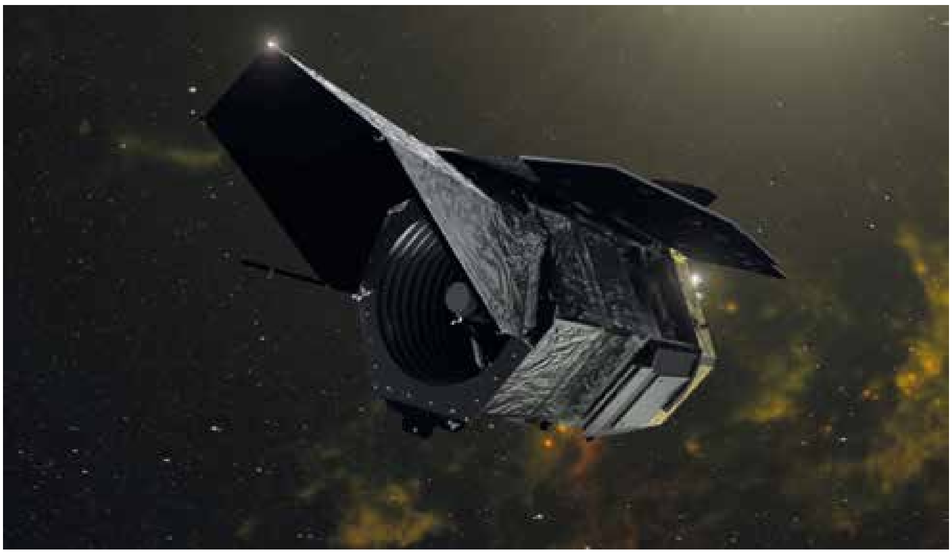
The Nancy Grace Roman Space Telescope (formerly the Wide Field Infrared Telescope, WFIRST) has been under development for about a decade under the direction of NASA. This space telescope employs a Hubble-sized primary mirror. The Roman Space Telescope is named after the astronomer Nancy Grace Roman, who led astronomical research programs at NASA for decades. Among other things, she was responsible for the scientific planning for the Hubble Space Telescope. The launch of the Roman Space Telescope is planned for 2027.

One of the two scientific instruments is the Coronagraph Instrument (CGI), in whose construction the MPIA is playing a major role. The CGI is a technology demonstration instrument that will allow astronomers to test high-performance techniques for detecting and characterizing faint exoplanets by direct imaging. If, as expected, the CGI reliably detects gaseous planets similar to Jupiter close to their parent stars, this observational technique could be used by future space telescopes to find and study rocky planets like Earth.

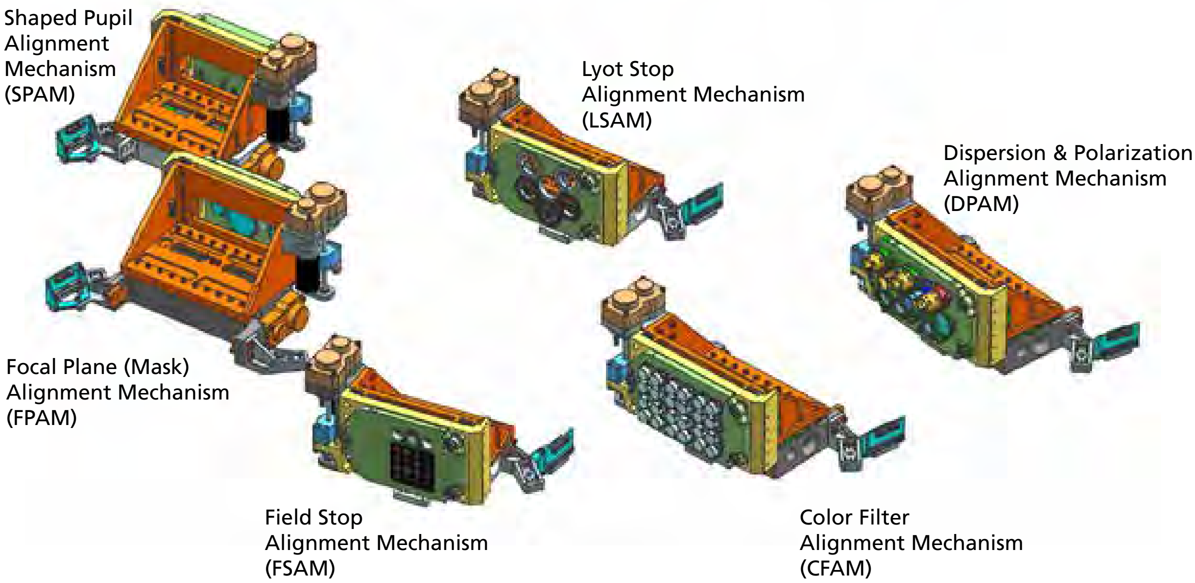
As an international partner of the Jet Propulsion Laboratory (JPL) at the California Institute for Technology (CalTech), MPIA supplies the six Precision Alignment Mechanisms (PAMs) that align and stabilize the CGI's optical components. The drives consist of x/y stages that move and fix the optics during observations.

NASA and JPL made it clear that a key motivation on their part to ask MPIA to build these crucial components of the Roman Space Telescope was MPIA's outstanding performance in the design and manufacture of the mechanisms for the James Webb Space Telescope. Engineers at MPIA designed the PAMs and manufactured them in MPIA's own precision mechanics workshop. Oliver Krause, head of the Infrared Space Astronomy Research Group, and his team will deliver the PAMs in 2022.

Fig. IV.2.5: Rendering of the Nancy Grace Roman Space Telescope.



Credit: GSFC / SVS

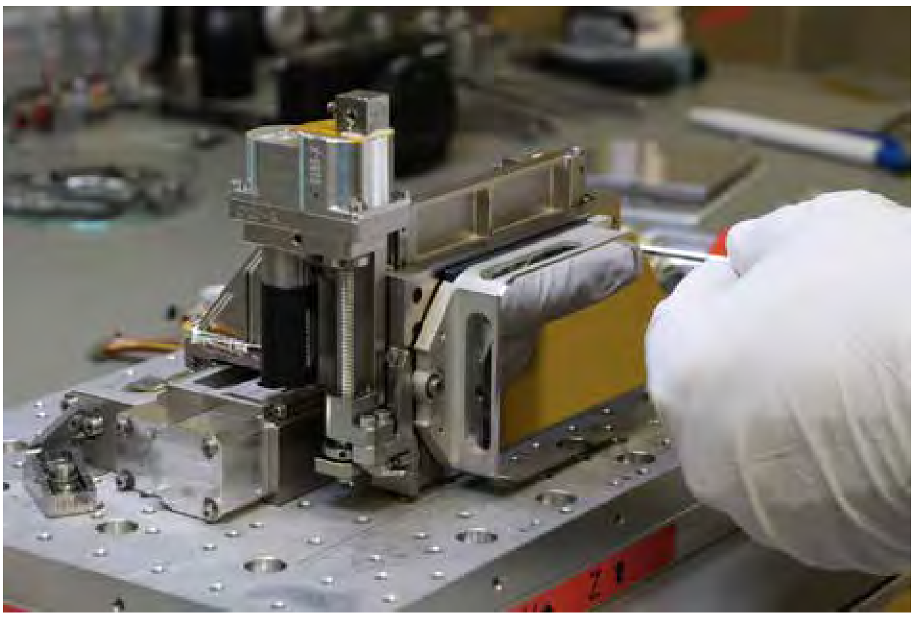


Credit: Ilya Poberezhskyi et al., Proceedings of the SPIE, Volume 11443, id. 114431V 22 pp. (2021)

Fig. IV.2.6: CGI Precision Alignment Mechanisms, shown with masks, stops, filters, and prism assemblies that each one will carry.

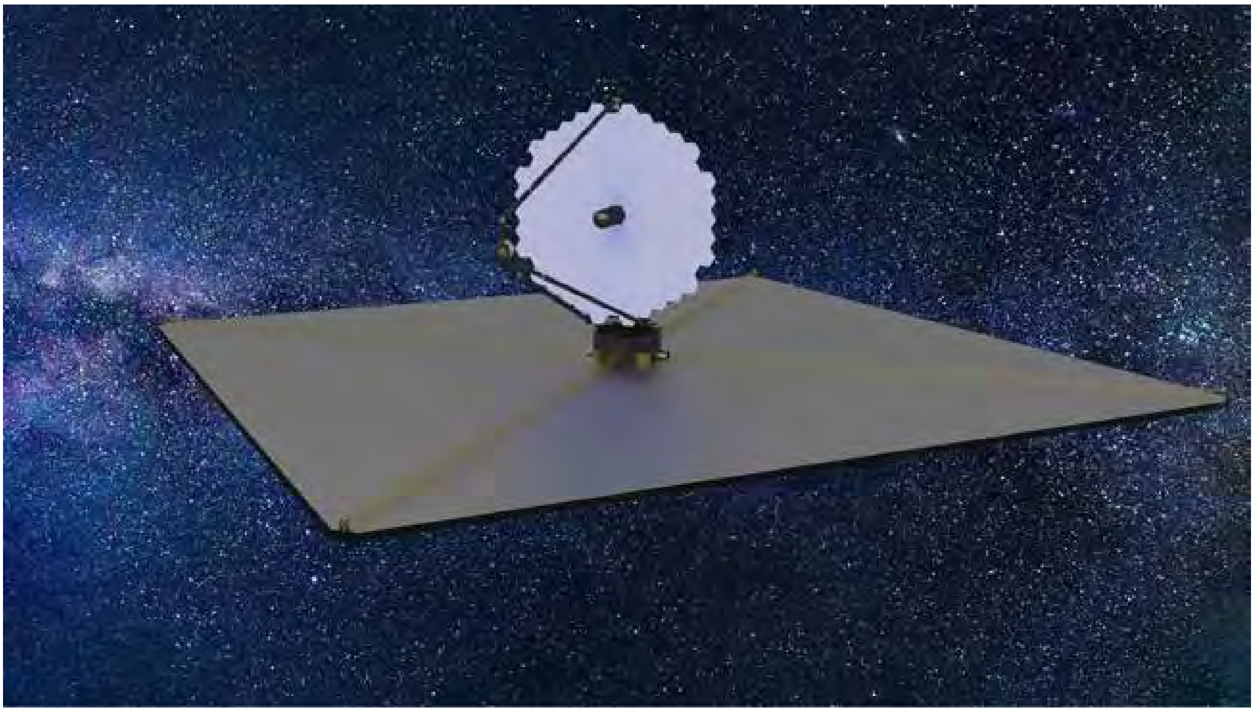
The CGI combines two observational techniques, coronagraphy and adaptive optics. A coronagraph is a common device that allows observers to block the light from bright objects by introducing a suitable mask into the optical path of the telescope. Once the bright light is blocked, fainter celestial bodies in close vicinity to the bright object become visible. Today, this method is already being used to detect exoplanets by direct imaging. However, the masks used in the process sometimes lead to strong image artifacts. As a result, possible exoplanets that reflect the light of their parent star can only reliably be detected at relatively large distances from their host stars. Currently, astronomers utilize this method almost exclusively to find giant planets made of gas, similar to Jupiter, at a relatively large distance from the central star.

To minimize the artifacts and allow for higher brightness contrast between the star and the planet, the CGI uses adaptive optics. This technology is often found in telescopes on the Earth's surface, where it optimizes the light we receive from an astronomical object by measuring the wave of incoming light and making rapid, real-time adjustments to deformable mirrors that reduce the blurring introduced by the light's passage through Earth's atmosphere. For the CGI, the same technology ensures that interference effects from the telescope's optical



Credit: O. Krause / MPIA

Fig. IV.2.7: The image shows one of the CGI Precision Alignment Mechanism Flight Models being assembled for tests in the MPIA labs.



Credit: NASA GSFC

Fig. IV.2.8: Rendering of the LUVOIR-A observatory with a 15-meter primary mirror design.

system are reduced. However, the computing power required for this is a new challenge for space cameras. Overall, scientists will be able to locate exoplanets closer than ever before near bright parent stars via direct imaging. The CGI is designed so that it would detect Jupiter as a point of light from a distance of about 30 light years. A built-in spectrograph then makes it possible to study the composition of these planets' atmospheres.

For this to succeed, the PAMs manufactured by the MPIA must ensure exceptionally high accuracy and stability in the positioning of optical elements such as filters, coronagraphs, and mirrors within a few nanometers, over time-spans of several hours. These requirements and the complexity of the CGI make it the most elaborate and expensive scientific instrument yet to be stationed in space. If the first tests in space meet the requirements, the CGI will be made available to astronomers to study exoplanets during the Roman Space Telescope mission.

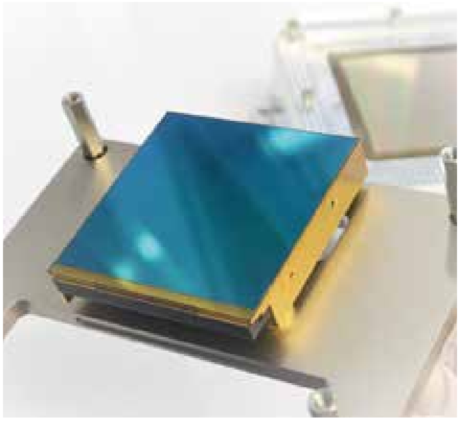
If the CGI mission is successful, the technology used could be further optimized for future missions such as LUVOIR, a planned 15-meter space telescope. Direct imaging of a second Earth would then be within reach, and would enable astronomers to examine the tenuous atmospheres of rocky, Earth-like exoplanets.

Oliver Krause, Head of Infrared Space Astronomy Research Group

IV.3 Instrumentation at MPIA

Overview of current projects

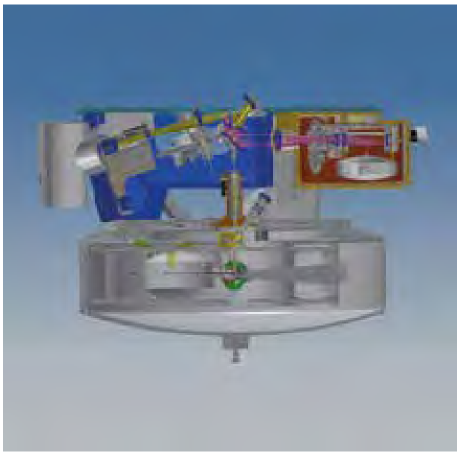
Astronomical instruments have different strengths and specializations. Here, we list **ongoing MPIA instrumentation projects for the year 2021**. Almost all of the instruments are cameras for producing astronomical images, spectrographs for analyzing the color components of light, or combinations thereof.



PANIC-4K

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

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



NTE

Nordic Optical Telescope Transient Explorer

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

LINC-NIRVANA

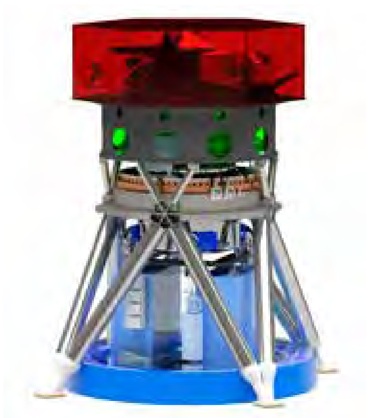
LBT INterferometric Camera –
Near-InfraRed Visual Adaptive interferometer for Astronomy

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

METIS

Mid-infrared ELT Imager and Spectrograph

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



MICADO

Multi-AO Imaging Camera for Deep Observations

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

4MOST

4-meter Multi-Object Spectroscopic Telescope

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

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

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

LVM TELESCOPES

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

CORONAGRAPH INSTRUMENT (CGI)

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

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

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

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

IV.4 Highlight Technical Departments

The optical design of the METIS Imager

METIS, the powerful Mid-infrared ELT Imager and Spectrograph for the Extremely Large Telescope (ELT), is one of the telescope's three first-generation science instruments. METIS successfully passed its optics final design review in July 2021, and is about to complete its final design phase.

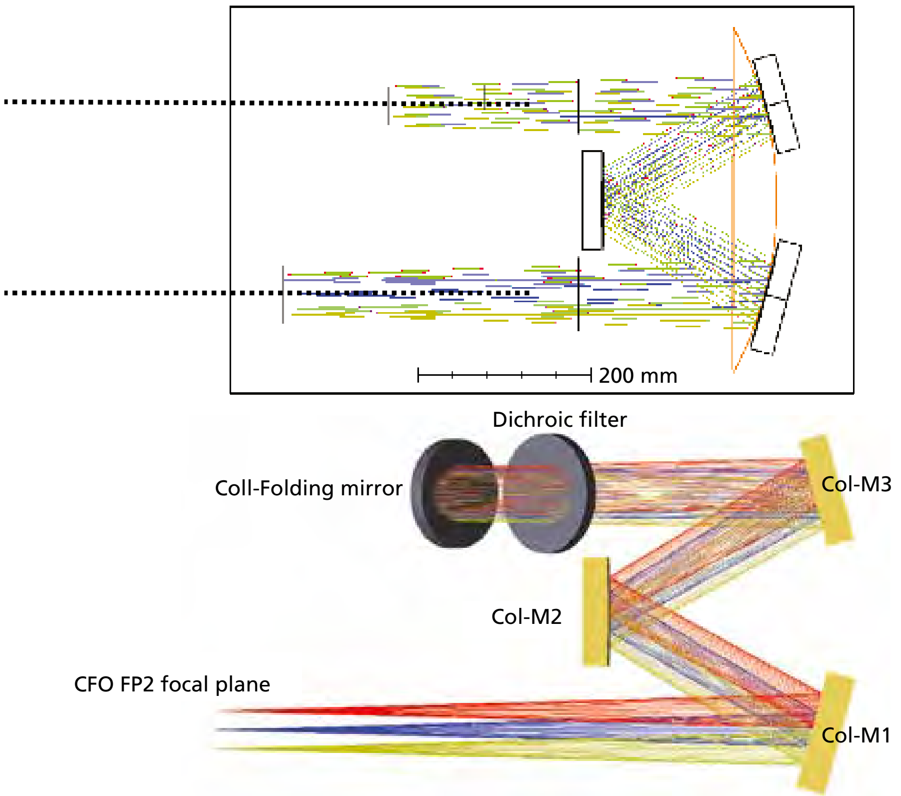
The instrument offers two separate units, an imager and a spectrograph. The different science operation modes are supported by an extreme adaptive optics system. Those subsystems, together with the Common Fore Optics (CFO), are entirely enclosed in a cryostat in order to maintain the stable low temperatures required for good performance at mid-infrared wavelengths. All subsystems work at 70 Kelvin, except the Imager, which operates at a mere 40 Kelvin.

The Imager subsystem provides diffraction-limited imaging capabilities and low/medium-resolution slit-spectroscopy in the mid-infrared wavelength regime, from 2.9 to 13.5 micrometers (covering the atmospheric bands L, M and N). In addition, the Imager provides a precise pupil re-imaging implementation. This allows for the positioning of high-contrast imaging masks for coronagraphic applications.

Two detectors, which are optimally suited for the corresponding wavelength ranges, encompass the complete bandwidth: a HAWAII-2RG for the L and M bands and a GeoSnap for N the band. The detectors operate at approximately 30 Kelvin.

In order to support these science detectors, the Imager design relies on two channels: one covers the L and M bands (between 2.9 and 5.3 micrometers) with a field of view of 11″×11″, whereas the other covers the N band (between 7.5 and 13.5 micrometers), with a field of view of 14″×14″. The field of view is based on an oversampling of the point spread function, optimized for high-contrast imaging in a fully AO-corrected field. The LM channel has an image scale of 5.47 milliarcseconds, while the N channel maps 6.67 milliarcseconds per pixel. The opto-mechanics operates at 40 Kelvin in order to provide detector-limited performance in both channels.

Fig. IV.4.1: Layout of final optical design of the Imager: the common collimator and the two cameras.



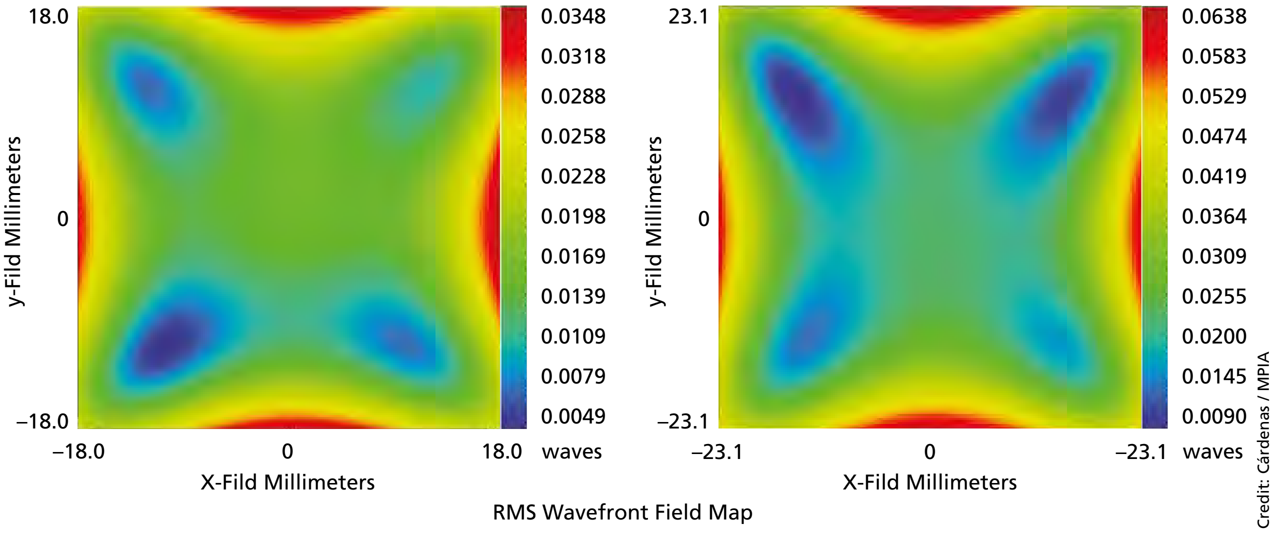


Fig. IV.4.2: End-to-end root-mean-square wavefront error at the detector. The LM channel has a mean value of 24 nm *(left)* and the N channel 44 nm *(right)*.

The Imager is a complex system that provides many functionalities in METIS. It took important choices in its design to make it easier to manufacture and align, and to provide outstanding optical quality. Firstly, the Imager design is strongly modular. Each functionality is handled by separate units. Both channels have a common collimator, fed by the METIS CFO and providing a collimated beam of 45 mm in diameter. Then, a cold dichroic splits the light into two channels feeding the L&M camera of the Imager as well as its N band camera. The dichroic transmits the L and M bands and reflects the N band.

For each channel in the collimated beam, the required components can be introduced by a wheel mechanism: cold stop masks; science filters for wavelength selection; grisms for low- or medium-resolution spectroscopy covering the individual bands L, M and N; and dedicated coronagraphic masks for high-contrast imaging.

Downstream of the collimated beams are the respective camera and detector. In practice, the design also includes several additional flat fold mirrors in order to bend the optical path toward the cold optics of the Imager. Furthermore, to provide pupil re-imaging capability for each channel, a pupil re-imaging system (consisting of a lens doublet made of Zinc Selenide and Zinc Sulphide) can be inserted between the camera exit port and the detector. It serves to image the pupil planes to the detector plane. Fig. IV.4.1 shows the optical arrangement of the Imager's final optical design.

Secondly, key choices had to be made for the optics. Key characteristics are: reflective optics, three-mirror anastigmat (TMA) configuration and freeform optics. This optical design delivers an excellent image quality over the complete field of view. As an example, Fig. IV.4.2 shows the wavefront error expected at the detector for both channels. The wavefront error accounts for the optical quality of a system, and is a way to measure the wavefront aberration, the smaller the better.

The optical concept is based on completely reflective optics due to the wide wavelength range to avoid chromatic aberrations. All mirrors are gold coated to provide a high reflectivity at infrared wavelengths. The collimator and the two cameras are TMA systems. This kind of optical system consists of three curved mirrors that minimize the three main optical aberrations, i.e. spherical aberration, coma and astigmatism.

In addition, all mirror surfaces are freeform, defined as Zernike surfaces with coefficients up to the 14th term. Typical traditional optical surfaces are spherical or limited to certain types of aspherical surfaces. A free-form optical surface has no translational or rotational symmetry about axes normal to its mean plane, which means it has more degrees of freedom than traditional optics. The use of free-from optics reduces the number of elements in an optical system, allows producing systems that are more compact and enables a very good optical quality along the complete field of view. Their manufacture is similar to that of highly complex aspheres.

Generating freeform surfaces requires processes such as coordinated axis diamond turning, which have higher degrees of freedom than the traditional processes (such as grinding and polishing). The surface form and the local slope change are factors that influence the complexity of the surface shape, its fabrication and its measurement. During the design of a free-form, it is imperative to take into account the limitations of the actual manufacturing process that is used. For that reason, in the case of our mirrors the grade of aspherization was limited to be smaller than 0.6 millimeters and the slope smaller than 30 milliradians.

Thirdly, a few more choices that concern the optomechanics make the optics easier to integrate and align. For the integration and alignment of the Imager, the collimator and the two cameras are considered as three

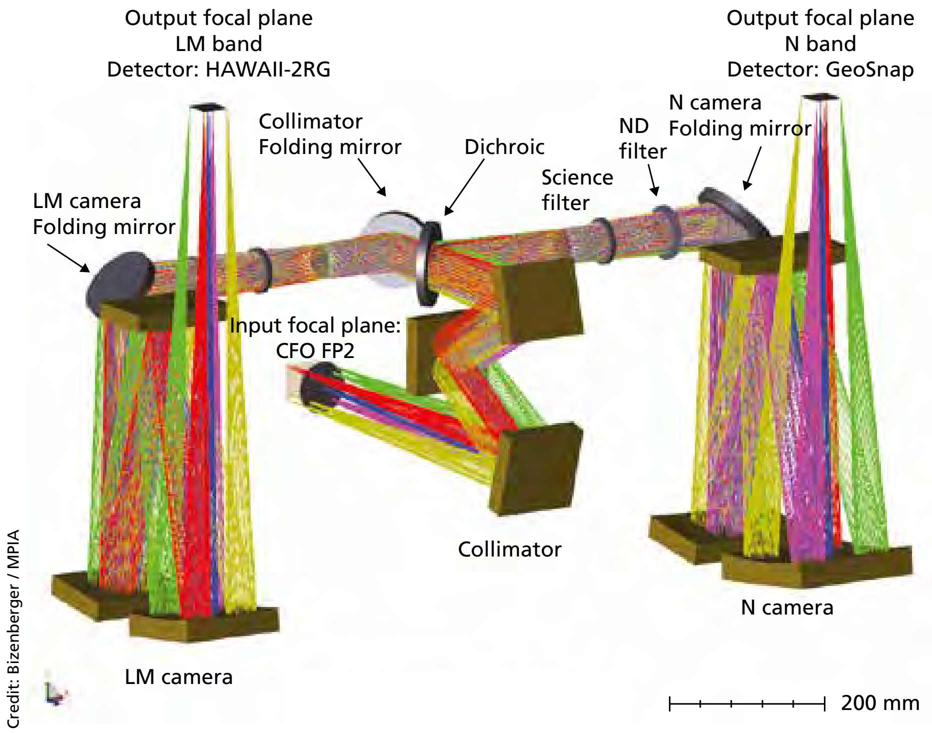


Fig. IV.4.3: Arrangement of the three mirrors. M1 and M3 share a close common curve that allows a common substrate for manufacturing. Input and output axes are parallel.

pre-aligned units with reference planes for mechanical position. They are aligned at room temperature and later, their performance is verified in the cold, i.e. 40 Kelvin, in a dedicated test cryostat to be built. To secure this plan, it is essential to create an athermal design. For this, the athermal optics were selected to be metallic, the mirrors are made of post-polished aluminium.

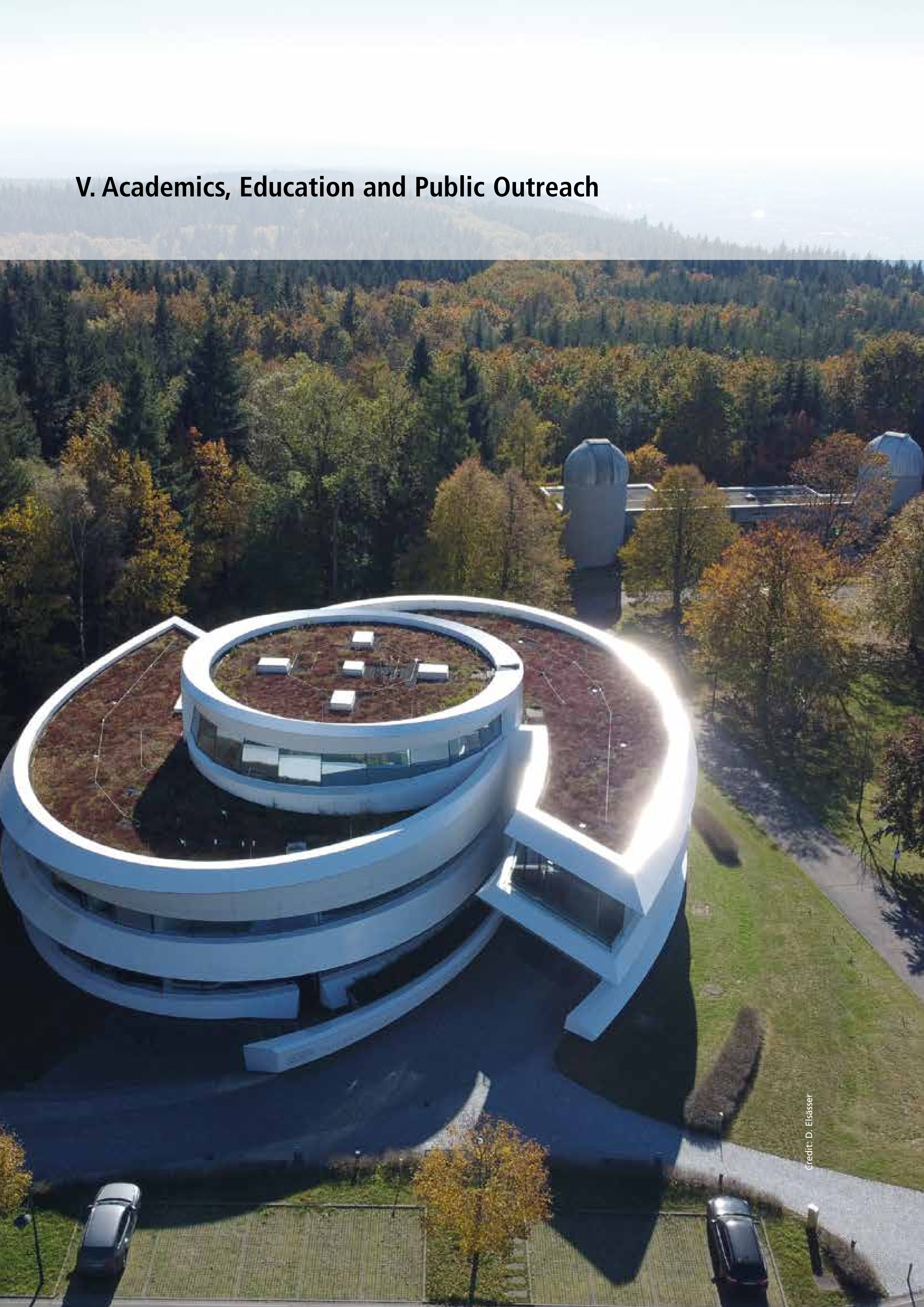
To reduce the degrees of freedom during manufacturing and alignment of each TMA, the first and the third mirrors of the anastigmat are designed to share a common substrate. This strategy yields a relative mechanical precision in the micrometer range (Fig. IV.4.3).

In order to reduce the mechanical volume of the Imager, the input and output axes were forced to be parallel, providing two important benefits: a more compact design and an easier alignment of each TMA (Fig. IV.4.1 and Fig. IV.4.3).

To conclude, these optics provide diffraction-limited imaging performance and allow for diffraction-limited spectroscopy in the complete wavelength range as well the required pupil performance for high contrast imaging. Furthermore, the opto-mechanical considerations taken into account during the design of the optics make the system easier to manufacture and align, compact and able to achieve a high performance.

M. Concepción Cárdenas Vázquez, Peter Bizenberger

V. Academics, Education and Public Outreach



Credit: D. Elsässer

V.1 Overview

Academics

As a research institute, MPIA takes its responsibility for fostering future generations of scientists seriously. Our main focus in that area is on the training of doctoral students. Here, the International Max Planck Research School for Astronomy & Cosmic Physics at the University of Heidelberg (IMPRS-HD) plays a central role – at MPIA, but also at the other astronomy-related institutes in Heidelberg. The IMPRS-HD organizes the application and selection process for the new students, fosters interaction between the students during IMPRS seminars and retreats, offers help with everyday administrative problems, and also offers a social network, in particular for foreign students who may arrive from far-away destinations. Heidelberg University contributes significantly 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.

IMPRS-HD was founded in 2004 as one of the first graduate schools in Heidelberg. It was established in close cooperation between the Heidelberg astronomical institutes. The main goal at that time was to establish a high quality teaching and training program, especially in English, which would succeed in attracting some of the best PhD students from all over the world to Heidelberg. It was also intended to provide an international environment for doctoral candidates from Germany. In Summer 2021, IMPRS-HD handed in a proposal for an enhanced continuation of the school, IMPRS-HD+, for short. The proposal was approved in November 2021, by a commission formed by the Max Planck Society (MPG) and the German Rectors' Conference (Hochschulrektorenkonferenz HRK, the alliance of German university leaders), with the Max Planck president citing the program's "proven and globally recognized excellence" as the reason why an extension "is logical in view of its outstanding success over the past decade and a

Fig. V.1.1: This year's IMPRS retreat took place in Heidelberg University's "International Academic Forum Heidelberg".

Credit: C. Fendt / MPIA

half." IMPRS-HD+ is now scheduled to start on January 1, 2023. It will be funded by the MPG with €420 000 per year. In addition to funding doctoral positions, the funds also support the organization of conferences, special teaching opportunities and traveling.

In parallel with these new developments, the regular IMPRS-HD activities continued in 2021 – the school's 17th year of activity, with the arrival this year of the so-called "17th generation" with a total of 29 new IMPRS students having arrived in 2021. Just as in earlier years, almost half of the new students (i.e. 12) are members of MPIA: Jan Eberhardt, Lukas Eisert, Philipp Eitner, Nils Hoyer, Markus Kuhlberg, Dhruv Muley, Klaus Paschek, Marten Scheuck, Luzian Seeburger, Yash Sharma, Molly Wells, Xiangyu Zhang. The single IMPRS fellowship 2021 was awarded to Philipp Eitner, who is doing his PhD at the MPIA under the joint supervision of Maria Bergemann and Hans-Walter Rix.

Overall, the IMPRS had received a total of 306 applications this year, for starting dates in 2022. Of those 306, 36% were applications from female students. It is quite usual for a similar proportion of female applicants on the short-list; what is unusual is that, by chance, this year, the proportion was exactly the same: 36%. In the strongest applicant group, namely the applications that were ranked as "A+" (in total 29), there were 33 % female students, and in the subsequent class "A" (with a total of 50 applicants), 48%. Numerous applications arrived from India (101), China (19), France (9), Brazil (10), Italy (18), or Chile (13). From Germany we received 37 applications. Note that these numbers consider the origin of the application (the institution of the MSc/BSc student) and not the citizenship of the applicant.

Nineteen IMPRS students completed their doctoral degree in 2021. The MPIA students among them are listed in Table V.1.1.

The 2021 IMPRS-HD summer school was on the topic of "Stellar Ecosystems". The scientific program was organized by Saskia Hekker (HITS), Andreas Quirrenbach (LSW) and Friedrich Roepke (HITS), with a high-caliber roster of invited lecturers: Conny Aerts (KU Leuven), Leen Decin (KU Leuven), Robert Izzard (U Surrey), Beate Stelzer (U Tübingen) and Achim Weiss (MPA Garching). Due to the still ongoing Covid pandemic, the school was held again as an online event. A positive side effect – that was already present in the 2020 virtual school – was the large number of participants: 109.

While training graduate students is the focus of MPIA's academic involvement, our activities begin much earlier, namely at 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 involved in teaching the Cosmology Block Course (Annalisa Pillepich) and the lecture on Fundamentals of Radio Astronomy (Fabian Walter) while Coryn Bailer-Jones gave a lecture on the physics of interstellar travel. MPIA also offers bachelor and masters students from Heidelberg University or from other universities the opportunity to conduct research for their theses at the institute. For students who want to gain research experience, there is a successful international summer internship program (coordinated by Bertram Bitsch).

Christian Fendt

Table V.1.1: PhDs completed by MPIA students in 2021.

Name	Defense Date	Title	Supervisor
Victor Marian	28.04.21	The Intricate Connection Between Major Mergers and AGN with the Highest Eddington Ratios	Jahnke
Felix Bosco	01.07.21	Probing the Growth of Black Holes at the Limit of Large Telescopes	Pott
Francisco Aros Pinochet	06.07.21	Towards a robust detection of intermediate-mass black holes in globular clusters	van de Ven
Diana Kossakowska	08.07.21	Modeling and Determining Origins of Signals found in Radial Velocity Data	Kürster
Martin Schlecker	21.07.21	The Architectures of Planetary Systems: Population Synthesis Meets Observations	Henning
Melanie Kaasinen	23.07.21	The Molecular Interstellar Medium in Distant Galaxies	Walter
Oliver Voelkel	16.12.21	On the Continuous Improvement of Global Planet Formation Models - The Consistent Formation of Planetary Embryos	Klahr

V.2 Academics, Education and Public Outreach

Public Outreach

In 2021, MPIA outreach remained for the most part in pandemic mode, with very few face-to-face and on-site activities – although we did welcome a couple of film teams recording on-site for broadcasts featuring MPIA research. The numerous education and outreach activities carried out at Haus der Astronomie (HdA), our center for astronomy education and outreach on MPIA's Königstuhl campus, operated by the Max Planck Society and administered by MPIA, were also in pandemic mode. A detailed description of HdA activities can be found in section IV.3.

Just as last year, our policy was to set the threshold for when to publicize publications in particular of MPIA postdocs and PhD students with a press release considerably lower than in previous, non-pandemic years. The rationale behind this was to counteract at least in part the lower exposure that postdocs and students would get for their work beyond their specialized sub-community, given that at the time, in-person conferences were severely restricted. All in all, we published 19 science releases this year, an increase of nearly 50% compared to the pre-pandemic year 2019.

A special event this year, for the institute in general but also in terms of public impact, was the launch of the James Webb Space Telescope (JWST) in December 2021 – easily one of the most widely anticipated events in astronomy and spaceflight. MPIA's crucial technological contributions to two of the JWST instruments, MIRI and NIRSpec, warranted correspondingly extraordinary outreach activities. These were coordinated with ESA and NASA via frequent online meetings. Unfortunately, we had to abandon plans for a public launch event in Heidelberg due to the pandemic situation at the end of the year. We did, however, publish a press release focusing on MPIA's technological flagship, the MIRI filter wheel, accompanied by an electronic press kit with numerous pictures and videos. Footage showing in action the qualification model of the MIRI filter wheel, which is located in the institute's infrared lab, received a total of 12 000 views on YouTube. Our pre-launch campaign to publicize MPIA's contributions managed to pique the interest of a number of media outlets: We were featured in an episode of the well-known German podcast WeltraumWagner (hosted on hr inforadio), and MPIA involvement was covered in two TV reports on the launch, including interviews and other footage filmed on-site. One of the reports was a feature as part of the German science magazine "nano", broadcast on 3sat.

Later, on the day of the launch, some of these video clips appeared on German national news programs. Overall, the JWST launch, including our own outreach efforts, generated broad interest in the domestic and international press, leading to over 40 additional stories featuring MPIA, seven of them on TV and streaming portals. Notable examples include coverage in the New York Times, and an episode of Terra X Lesch & Co. that featured MPIA director Thomas Henning as a virtual guest, and gathered almost 500 000 views on YouTube.

In addition to having contributed to the JWST itself, MPIA astronomers are also leading and/or involved in JWST observing programs. We publicized their research plans and aspirations for JWST observations in eight short videos featuring MPIA astronomers who explain their JWST research plans in one-minute long videos published on the MPIA YouTube channel. The videos are in each scientist's native language, with subtitles in English and German.

Fig. V.2.1: MPIA director Thomas Henning and Oliver Krause as lead scientist of MPIA's Infrared Space Astronomy Group on the nano episode on the JWST aired on 17 December 2021.

Credit: 3sat

Our supporting public relations campaign for MPIA's contributions to JWST continued directly into early 2022, when in the second week of January, a thread of tweets about the MIRI filter wheel and MPIA's contribution to that part of the instrument went viral, gathering 360 000 views and 17 000 interactions, and quickly boosting MPIA follower numbers on Twitter by more than 500.

As "Faszination Astronomie Online," Haus der Astronomie's online talk series, went into its second year, MPIA scientists once more contributed, featuring many of the institute's core research topics: institute director Thomas Henning took viewers on a journey from exoplanets to the origins of life, Miriam Keppler presented her impressive observations of the birth of new planets, while Nadine Neumayer's talk featured supermassive black holes in the centers of galaxies, among numerous other MPIA contributions. Coryn Bailer-Jones chose a more unusual topic, analysing the feasibility (or not?) of space elevators. The institute's activities in instrumentation were also well-represented, with Silvia Scheithauer talking about instrumentation for ESO's Paranal Observatory in Chile, Oliver Krause giving a pre-launch introduction to JWST, and Wolfgang Brandner explaining the fundamentals and applications of Adaptive Optics. This year, the talk series also featured MPIA's Laboratory Astrophysics Group, based at the University of Jena, with Cornelia Jäger presenting an introduction to the goals, techniques and results of laboratory astrophysics.

Within the newly started "Science in the city" series initiated by the city of Heidelberg, the Haus der Astronomie took a leading role in organizing a unique event aimed at promoting the visibility of astronomical research in Heidelberg. From December 6th 2021 until January 27th 2022, all institutes featuring astronomical research in Heidelberg presented themselves at a location mid-town. This was a joint endeavour of MPIA, HdA, the Max Planck Institute for Nuclear Physics (MPIK), the Zentrum für Astronomie (ZAH) and the Institute for Theoretical Physics (ITP) of Heidelberg University, including the CRC 881 (SFB 881), as well as the Heidelberg Institute for Theoretical Studies (HITS).

The exhibition was presented in a gallery-style showroom and included informational banners from all the participating institutes, as well as video animations and exhibition elements such as telescope parts or models. Additionally, elements from the "Astronomy for Everyone" exhibition designed at HdA in 2018 were included in the showcase.

Due to the rising numbers of corona infections, unfortunately we couldn't proceed with the original "open-house" idea, which would have included regular talks as well as regular attendance of two astronomers on site. Instead, we were restricted to a shop-window exhibition, visible to passers-by. Although we do not have reliable estimates of visitor numbers, the prime location on Heidelberg's main street, next to both the theater and other popular meeting points, as well as the usually quite crowded time period leading up to Christmas, we can safely assume that our exhibition was seen by a considerable number of passers-by.

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

Fig. V.2.2: Science in the City: Window-shopping for astronomy in Heidelberg's pedestrian-only main street.

Credit: R. Hubele / HdA

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: to communicate the fascination of astronomy to the general public, to support astronomy education, and to foster the exchange of knowledge between scientists. The custom-built, galaxy-shaped building on the MPIA campus hosts an active team of astronomers and astronomy educators dedicated to developing and producing materials and resources for the public or for use in schools.

Just as most of the rest of the world, by the time 2021 came around, we were pandemic veterans – back in 2020, we had cautiously moved almost all in-person events online, and settled into a temporary long-distance mode of operations.

“Faszination Astronomie Online” – our online public talk series continues

The online public talk series “Faszination Astronomie Online” remained our mainstay of public outreach. Throughout 2021, we broadcast one talk each Tuesday and each Thursday, without fail. “Faszination Astronomie Online” talks are nominally 30 minutes, and it typically takes an additional 30 minutes to answer the audience’s questions. Our topics cover the whole range of astronomy. Highlights included Alfred Krabbe treating viewers to a live tour of the flying observatory SOFIA – at the time parked at Cologne airport, admittedly – and talks as diverse as observing from your own balcony, the future of our universe, primordial black holes, the physics of space elevators, X-ray echoes and exoplanet population synthesis.

Again, almost one third of our 2021 roster of speakers were women, once more thanks in large part to the #astrophysikerinnen list compiled by the astronomer Victoria Grinberg, a long-term Twitter thread listing women astrophysicists which is a treasure trove for finding German-language public speakers. Over the year, the Haus der Astronomie YouTube channel gained 2800 subscribers, growing from 4500 to 7300. All in all, in 2021, we had 105 online talks, with an average of 3000 views per video.

Our regular talk series was complemented by special events, namely Carolin Liefke talking about the Moon’s crater landscape in March and about the giant gas planets in October, each time on the occasion of one of the two nation-wide “Astronomy Days” organised by Vereinigung der Sternfreunde, Germany’s umbrella organisation for amateur astronomers and their local and regional observatories and astronomy clubs.

Reaching the public – online or offline

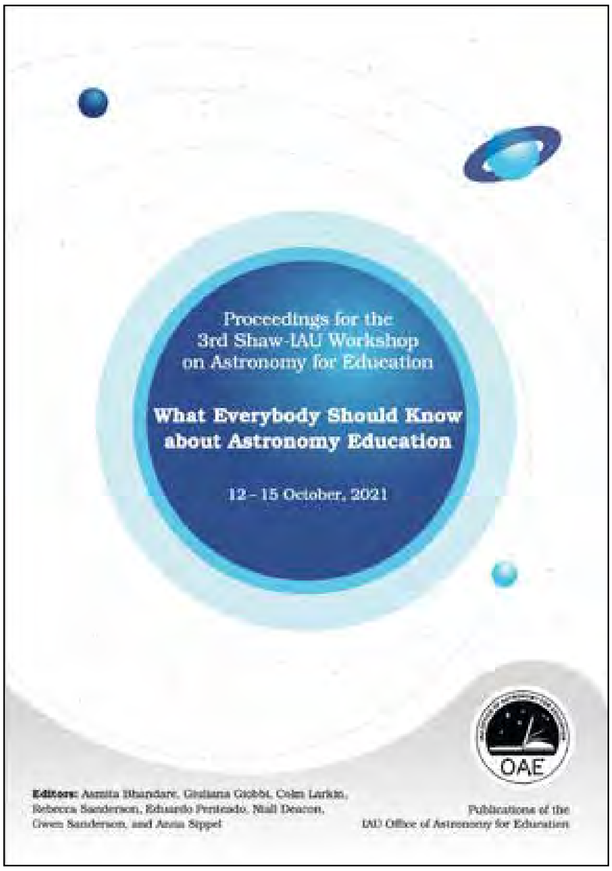
There were a number of occasions beyond our flagship talk series where we offered events to the public. Following HdA tradition, we again participated in “Explore Science,” the open-air science event organised by the Klaus Tschira Foundation – one of the partners be-

Fig. V.3.1: Examples of announcement tiles created by Carolin Liefke for talks given as part of the “Faszination Astronomie Online” lecture series.

hind HdA – in Luisenpark in Mannheim, which had been moved to October from its usual spring date due to the pandemic situation. Since the event's theme that year was chemistry, Natalie Fischer, in collaboration with Astronomieschule e.V., prepared an interactive exhibit for elementary-school-age children on "The stuff that stars are made of."

The 35 public talks that HdA staff members gave this year were almost without exception online, some hosted at locations as diverse as Florence, Hamburg, Rüsselsheim, and Dodoma in Tanzania.

Every winter term, HdA managing scientist Markus Pössel offers lectures under the heading "Astronomie für Nichtphysiker," literally "astronomy for non-physicists," for non-physics majors at Heidelberg University – complementing the summer term general introduction to astronomy and astrophysics taught by colleagues from the Zentrum für Astronomie and MPIA. The 2020/2021 lecture on Einsteinian Astrophysics was fully virtual from the start, while the fall 2021 lecture on compact objects started out cautiously as an in-person event in October, then went online as pandemic conditions worsened again.



Credit: OAE

Fig. V.3.3: The proceedings of the 3rd Shaw-IAU Workshop on Astronomy for Education are basically an introductory textbook "Astronomy Education 101" – in particular in combination with the videos from the workshop's talks and posters.

Mostly online teaching, workshops, courses, lectures, internships

Another sector that went almost completely online this year were our events for pupils – from kindergarten to high school –, university students and in-service teachers. We had two courses that were part of pre-service teacher training at Heidelberg University. One was our traditional PASTRO course for bachelor students, which provides budding teachers with basic knowledge of astronomy and astrophysics. The other was a first: the ADIDA astronomy education module for teachers who, in addition to the two required teaching subjects, voluntarily choose astronomy as their third subject. ADIDA consists of basic lectures provided by Olaf Fischer, and a practical part working with school students, which was facilitated and supervised by one of our HdA teachers, Matthias Penselin. Natalie Fischer's basic astronomy seminar for future elementary school teachers at Heidelberg's University of Education was also a fully online event.

This year's Girls' Day, part of a nation-wide day to get school-age young women interested in professions where women are as of yet underrepresented, was a virtual rally through our galaxy-shaped building, with astronomy-related riddles for participants to solve. While high-school level workshops were on hiatus, Esther Kolar successfully developed virtual workshops for Kindergarten-level groups, running 19 such workshops this year – plus an extended multi-day workshop for a special needs school. A special occasion was Natalie Fischer's observation of the partial solar eclipse mid-June with students from our elementary-school partner school, Schillerschule Walldorf.

While our international summer internship program was on hiatus this year, HdA staff did mentor several students – from Hector Academy research projects to a Jugend forscht science fair project to the astrophysics working group of the Heidelberg Life Science Lab. We also offered two online and one in-person one- or two-week-long internships for high school students over the year. Carolin Liefke also continued her collaboration with the IASC asteroid search campaign for high-school students, supervising three campaigns with groups from Germany. She also continued to support German groups interested in remote observations with the Faulkes telescopes at Las Cumbres Global Observatory.

Near the end of the year, we cautiously reinstated on-site training events: From October to December several parts of a teacher training for kindergarten teachers in collaboration with Forscherstation Heidelberg, and in mid-November our nationwide WE Heraeus Teacher Training on astronomy and astrophysics for high-school teachers, funded by the WE Heraeus foundation. To the best of our knowledge, we were sufficiently cautious for neither event to contribute to the spread of SARS-CoV2.

In addition, we participated in training events hosted by collaboration partners – notably on-site training workshops for kindergarten, elementary school or secondary school teachers, at Forscherstation Heidelberg, Sternwarte Sonneberg, ESO Supernova Garching, the Rhoeniversum in Oberelsbach or Baden Württemberg's central teacher training base at Bad Wildbad. Virtually, we participated in a teacher training event in the Rhineland-Palatinate, and the MINT Pupil's Congress in Kassel. Carolin Liefke, with Dominik Elsässer, again taught a course to particularly interested students at Science Academy Baden-Württemberg, this time on radio astronomy.

Fig. V.3.3: *Top left:* First place, category Comets: Neowise's metamorphosis, by Tomáš Slovinský and Petr Horálek, Slovakia. *Top right:* First place, category Light pollution, Starry Night over Eifel national park by Dong Han, China. *Center left:* First place, category Meteor showers: Geminid Meteor Shower from China, by Dai Jianfeng, China. *Center right:* First place in the IAU OAE Astrophotography Contest, category Star trails: Half day exposure to the north star, by Fabrizio Melandri, Italy. *Bottom left:* First place, category Sun/Moon haloes: Selene meets the Moon, by Sheila Wiwchar, Canada. *Bottom right:* First place, category total lunar eclipse: The eclipsed Moon sets near the Rochetta di Prendera, Dolomiti Unesco, by Alessandra Masi, Italy. All six images are licensed under the Creative Commons license CC BY 4.0.


Credit: T. Slovinský and P. Horálek / IAU OAE


Credit: D. Han / IAU OAE


Credit: D. Jianfeng / IAU OAE


Credit: F. Melandri / IAU OAE


Credit: S. Wiwchar / IAU OAE


Credit: A. Masi/IAU OAE

Creating resources and gaining followers

As in previous years, creating resources for astronomy education and outreach was an important part of our activities. "Wissenschaft in die Schulen!" (literally "Science into Schools!"), coordinated by Olaf Fischer, produced 18 contributions this year, each providing teaching resources that are linked to a specific, current topic of astronomical research. For his long-term work on "Wissenschaft in die Schulen!", Fischer received this year's Hanno-und-Ruth-Roelin Prize for Science Communication from the Max Planck Institute for Astronomy.

Natalie Fischer developed two online learning environments, one on constellations, the other on eclipses, for Forscherstation Heidelberg. She also published her simple model of "One Million Earths inside our Sun" – one million small spheres inside a larger transparent one, to illustrate the relative sizes of the Earth and the Sun – on the IAU astroEDU portal. An image of that model had already gone viral on various social media over the past years, although sadly in most of those cases without attribution. Fischer also developed the activities and accompanying material for an astronomical "Advent Calendar" for children in collaboration with the famous mouse from "Sendung mit der Maus" for Christmas 2021.

In 2020, as a deliberate decision to boost resources that would be accessible online during pandemic time, but also beyond, we had begun developing AstroApps – browser-based apps illustrating, and allowing for the interactive exploration of, fundamental astronomical concepts and phenomena. This year saw the implementation by Thomas Müller of new apps about solar eclipses, horizontal sundials, stellar parallax and binary star systems. Müller and Olaf Fischer also wrote "Wissenschaft in die Schulen" contributions – with descriptions of the AstroApps as well as background information and tips for using the apps in the classroom – for the Hertzsprung-Russell diagram app, the orbital elements app, and the star tracks app.

Markus Pössel was guest editor for a topical edition on cosmology for the astronomy education magazine Astronomie und Raumfahrt im Unterricht ("Astronomy and Spaceflight in the Classroom"), which introduced presented articles by various educators and scientists on how to teach about the fundamental topics of relativistic astrophysics: general relativity as a theory, black holes, gravitational lensing, gravitational waves, and cosmology. Pössel also contributed a chapter on teaching general relativity with simplified models to the collection "Teaching Einsteinian Physics in School," edited by Magdalena Kersting and David Blair, published by Routledge this year.

Carolin Liefke continued her outreach work for HdA on various social media channels, namely Twitter, Instagram, Facebook and YouTube, taking part in special collaborative events such as the Global Science Show in June (as a participant) and July (as co-organiser of a special astronomy-themed edition). For the July edition, she recruited several of the National Astronomy Education Coordinators of the IAU Office of Astronomy for Education, transforming the usually UK-centered event into a truly global one.

Networking – national and international

Focus point of our international networking was, of course, the International Astronomical Union's Office of Astronomy for Education, which HdA has hosted since late 2019. Over the course of 2021, our volunteer network of National Astronomy Education Coordinator (NAECs), who act as the main liaison between the OAE and their country's education stakeholders, grew from 300 NAECs from 82 countries to 352 NAECs from 99 countries. By the end of the year, our OAE was also supported by three "branch offices:" the OAE Center Italy, the OAE Center Cyprus and the OAE Node Nepal.

This year, OAE organised two major events. During the two days of the "IAU Offices Family Meeting" in July, we brought together (virtually, of course) members of all four of the IAU Offices (Astronomy for Development, Outreach, Young Astronomers, and ourselves) as well as their networks for an extensive getting-to-know-each-other, in order to foster future collaborations.

October saw the OAE's 3rd Shaw-IAU Workshop on Astronomy for Education, with the motto "What everybody should know about astronomy education." The workshop was in effect a large-scale "Astronomy Education 101," providing introductions to a great variety of aspects of astronomy education, from low-tech methods to astronomy education research to diversity and inclusion in teaching about astronomy. We were joined by 580 participants from 90 countries, and as the talks and posters themselves were made available on YouTube in the shape of a total of 122 videos, and their contents in (online and printed) Proceedings, the introductory resources for getting up to scratch in astronomy education are now widely available to members of the community.

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