Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report 2018

Cover Picture:

Our cover picture is not an astronomical image in the classical sense. Instead, it was based on measurements of nearly 1.7 billion stars, performed with unprecedented accuracy by ESA's astrometry satellite Gaia. The map shows the total brightness and colour of stars observed by the ESA satellite in each portion of the sky between July 2014 and May 2016. The second Gaia data release, DR2, published on April 25, 2018, was one of the most important events in recent astronomical history. Researchers based at the Max Planck Institute for Astronomy, led by Coryn Bailer-Jones, who are part of the Gaia's Data Processing and Analysis Consortium (DPAC), used Gaia's measurements to derive the physical properties of almost 80 million stars, making this the largest stellar census yet.

Credit: Gaia Data Processing and Analysis Consortium (DPAC); A. Moitinho / A. F. Silva / M. Barros / C. Barata, University of Lisbon, Portugal; H. Savietto, Fork Research, Portugal

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Contents

Preface

Our universe never ceases to amaze the human mind. It harbors an astonishing range of phenomena and conditions, it reveals an astounding level of self-organization and hosts an unimagined variety of other “worlds”. Through imaginative thought and hard work, supported by innovative tools for observations, astronomers improve their understanding of our universe year after year.

It is in this spirit that the Max Planck Institute for Astronomy pursues its research, with particular focus on galaxies and on stars with their planets. We develop and build instrumentation, we observe and model data through theory and computer simulations, all in pursuit of new ways of finding out how our cosmos works.

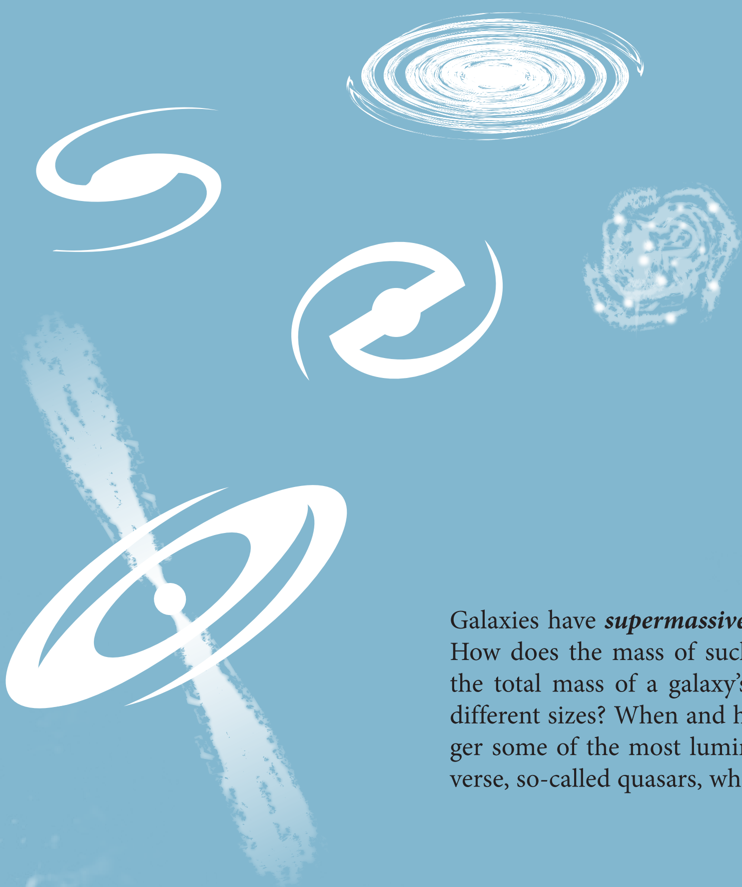
But like all research, our astronomy is people-driven. That is why MPIA is striving to build and foster an ambitious, enthusiastic and diverse community of excellent researchers, students and engineers. This report provides a summary of what we did at MPIA on the eve of the 50th anniversary of the institute’s founding.

Hans-Walter Rix , Thomas Henning

Heidelberg, August 2019

I. MPIA in a Nutshell

Our Fields of Research: Galaxies and Cosmology

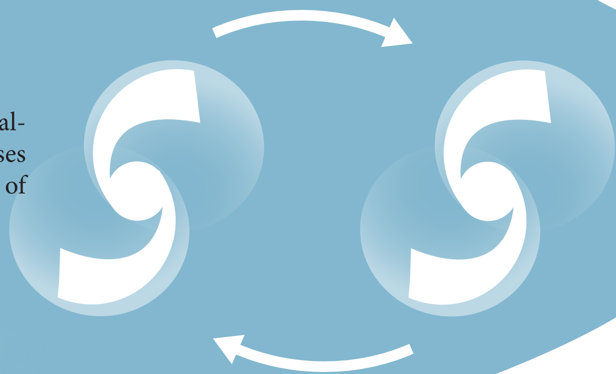


Galaxies come in many shapes and sizes. How do these differences arise? And what factors are responsible for how many stars a galaxy produces?

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?

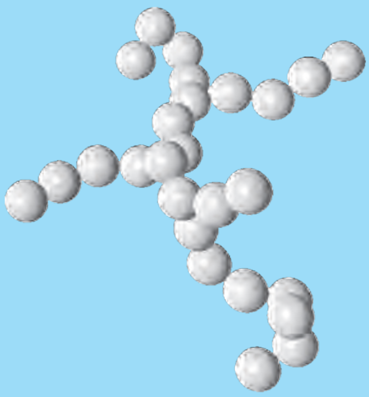


How are ***dark matter*** and hydrogen gas distributed on the largest ***cosmic scales***, across hundreds of millions of light-years? How is this distribution linked to the evolution of galaxies over billions of years? How did the complex structure of our Universe arise from an almost perfectly smooth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

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?

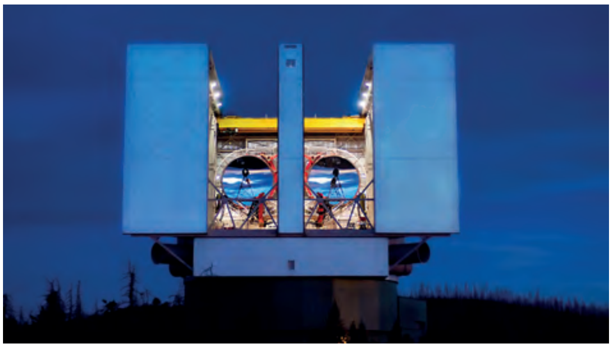
How do ***magnetic fields*** influence which clouds of the interstellar medium collapse to form stars? What is the role of turbulent motions within these clouds?



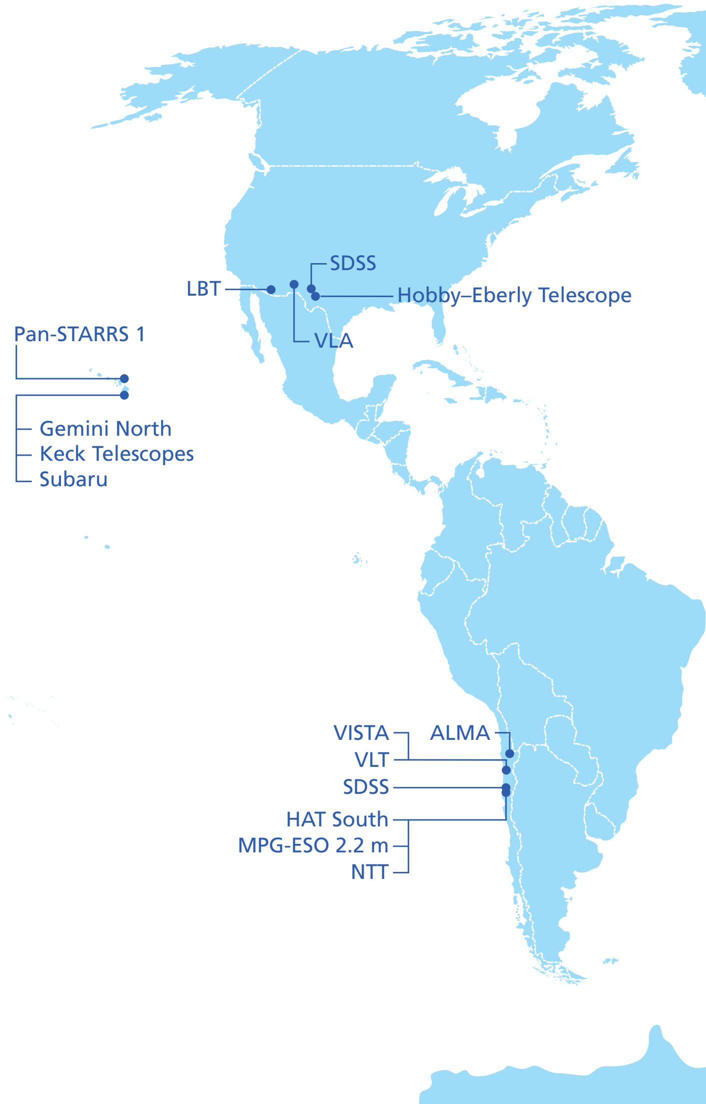
What are the ***stages of planet formation*** – from the first colliding ***grains of dust*** to objects thousands of kilometers across? What can laboratory experiments tell us about the properties of cosmic dust – and ways to detect these properties?

Since 1995, astronomers have discovered more than 4100 ***exoplanets*** (planets orbiting stars other than the Sun). What can these widely different planetary systems tell us about planet formation?

MPIA Telescopes all Over the World

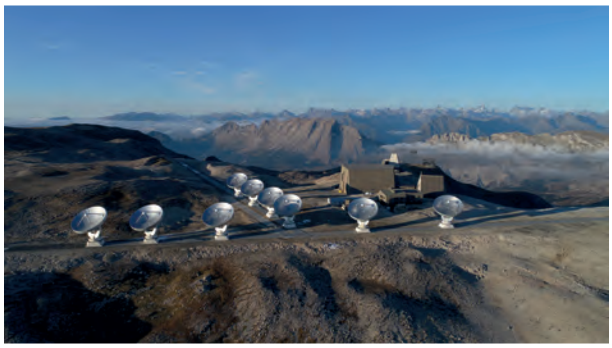


MPIA is part of the consortium operating the Large Binocular Telescope (LBT) on Mount Graham in Arizona. The LBT has two 8.4 meter mirrors on a single mount.



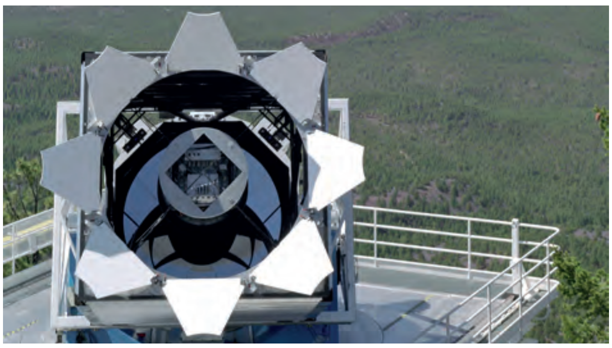
MPIA has been involved with constructing several instruments for ESO's Very Large Telescope (VLT). MATISSE saw first light in 2018.

MPIA researchers use the ALMA observatory at the Chajnantor plateau in the Atacama Desert to study some of the coldest and most distant objects in the Universe. ALMA is an interferometer for observations in the millimeter and submillimeter wavelength range at an elevation of 5000 m.



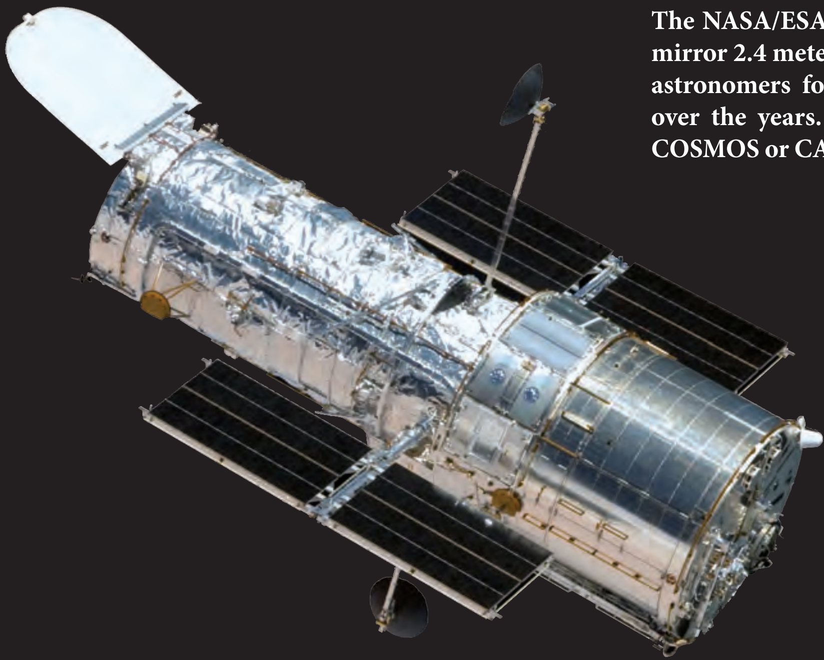
On the Northern hemisphere, MPIA researchers use the NOEMA millimeter array currently under advanced construction in the French Alps. The Max Planck Society is one of the founding partners of IRAM, the Institut de Radioastronomie Millimétrique based in Grenoble, which operates IRAM as well as a separate 30 meter radio dish in Spain.

Calar Alto Observatory in Southern Spain was founded in the 1970s by MPIA, and by 2018 was operated as a joint German-Spanish research center. In April 2019, the observatory passed fully into Spanish hands.



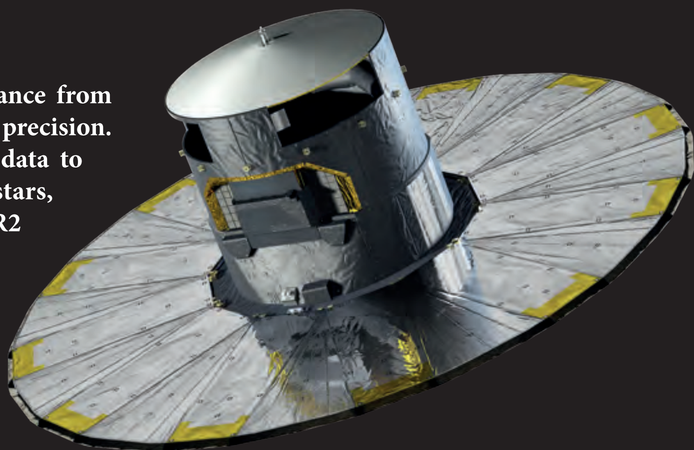
MPIA is a member of the Sloan Digital Sky Survey (SDSS), a spectroscopic survey using a 2.5 meter telescope in New Mexico. The survey gathers high-quality spectra of a large number of astronomical objects.

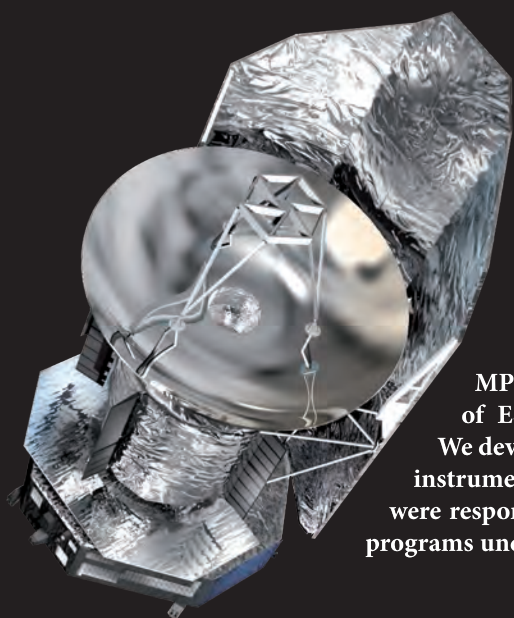
Space Telescopes



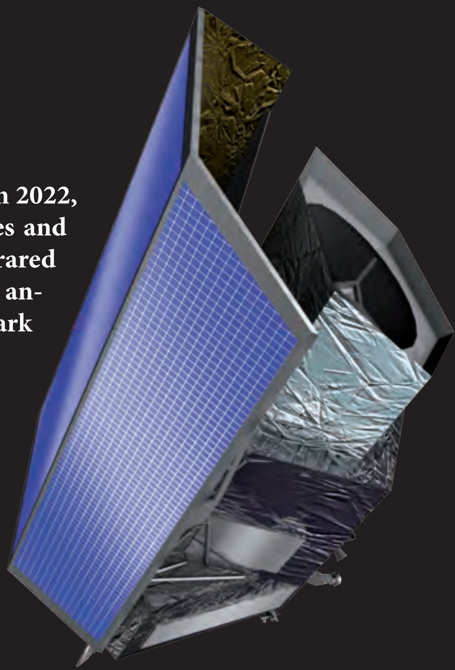
The NASA/ESA Hubble Space Telescope (with a main mirror 2.4 meters in diameter) has been used by MPIA astronomers for a variety of successful observations over the years. This includes larger surveys such as COSMOS or CANDELS that involve MPIA researchers.

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, and played a key role in the major data release DR2 published on 25 April 2018.

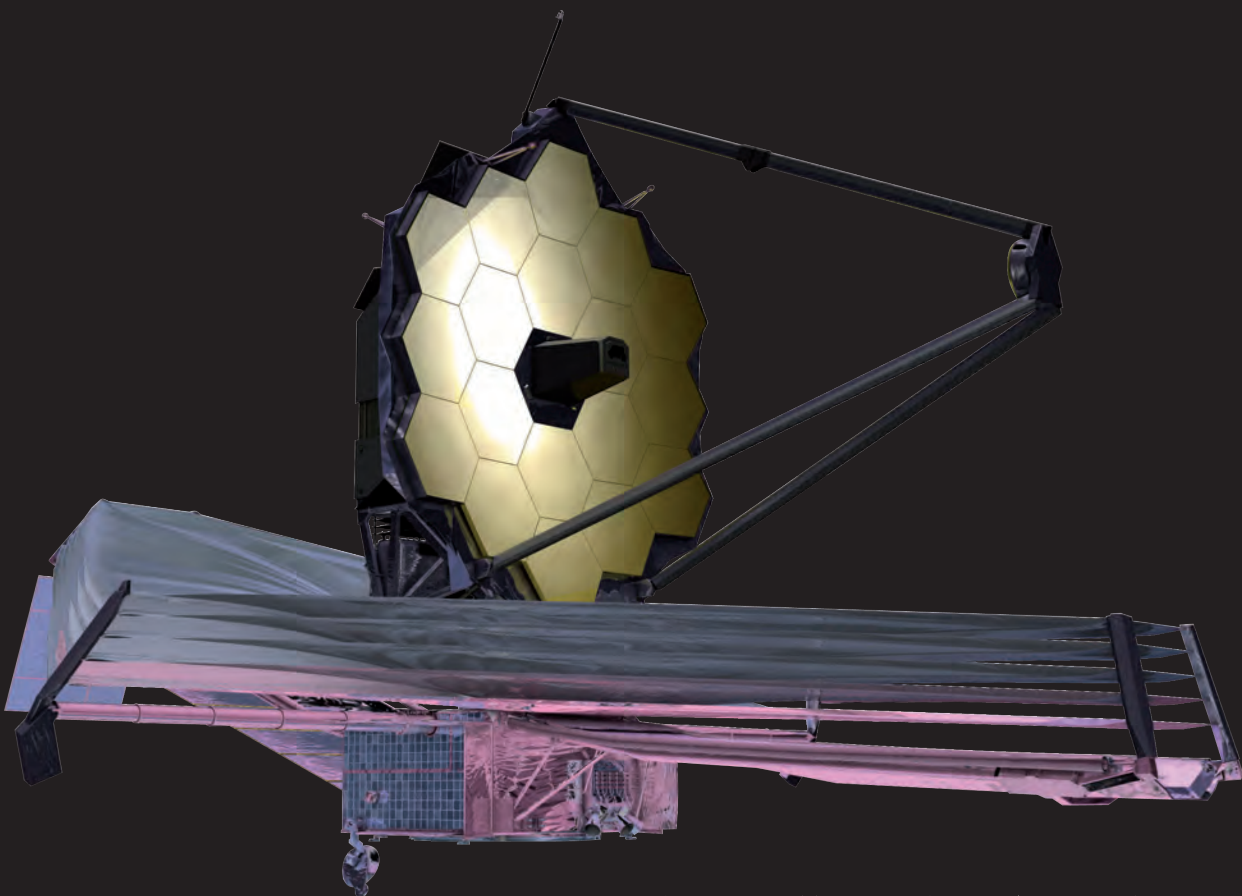




MPIA contributed to the construction of ESA's infrared observatory Herschel: We developed key components for the PACS instrument aboard the Herschel satellite, and were responsible for a number of observational programs undertaken with Herschel.



For ESA's Euclid mission, which is slated for launch in 2022, MPIA scientists have developed calibration strategies and are contributing to the construction of the near-infrared spectrometer and photometer NISP. Euclid is set to answer fundamental questions about the nature of dark matter and dark energy.



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

Major conferences organized by our staff members

The Early Phase of Star Formation EPoS 2018: Archetypes
13–18 May
Ringberg Castle, Tegernsee

The Metal-poor Galaxy: Spectroscopy, Stellar Composition, Astroarchaeology
2–6 July
Ringberg Castle, Tegernsee

Stellar halos across the cosmos
2–6 July
Haus der Astronomie, Heidelberg

Survival of Dense Star Clusters in the Milky Way System
19–23 November
Haus der Astronomie, Heidelberg

Chemical Evolution and nucleosynthesis across the Galaxy
26–29 November
Max-Planck-Haus, Heidelberg

Heidelberg-Harvard Workshop Physics of Star Formation
4–7 December
Haus der Astronomie, Heidelberg

Above: Poster of the Conference "Survival of Dense Star Clusters in the Milky Way System" at Haus der Astronomie, Heidelberg.
Below: Participants of the conference „Early Phase of Star Formation 2018: Archetypes", held at Ringberg Castle, Tegernsee.

Credit: Henrik Beuther

Major Grants and Awards

Credit: Artur Godlinski

Paola Pinilla

Dimitry Semenov and Thomas Henning
received the Cozzarelli Prize of the US National Academy of Sciences.

Paul Mollière
received the Max Planck Society's Otto Hahn Medal.

Asmita Bhandare
received the prize for best poster at the EPoS 2018 conference in Ringberg.

Paola Pinilla
received the Humboldt Foundation's Sofja Kovalevskaja award, which will enable her to set up her own research group at MPIA in 2019.

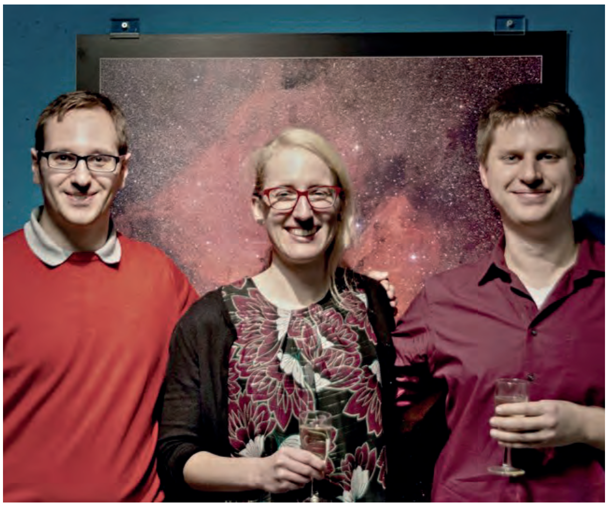
Nestor Espinoza
received one of the IAU Fellowships awarded by The Gruber Foundation in conjunction with the International Astronomical Union (IAU).

Tina Brill
was awarded the Max Planck Society's Trainee Prize.

Anish Amarsi
received the Charlene Heisler Prize awarded by the Astronomical Society of Australia.

Hubert Klahr
received a major grant from the DFG Schwerpunktprogramm 1833 "Building a Habitable Earth".

Nicolas Martin
received the Prix Espoir awarded by the Université de Strasbourg.



Credit: Sumeyye Suri ,MPIA

The Patzer-Award winners 2018: Mattia Sormani, Miriam Keppler und Michael Hanke (from *left* to *right*).

Patzer Prizes 2018

Michael Hanke, ZAH/ARI
for his publication "ATHOS: On-the-fly stellar parameter determination of FGK stars based on flux ratios from optical spectra" (2018, A&A, 619, A134).

Miriam Keppler, MPIA
for her publication "Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70" (2018, A&A, 617, A44).

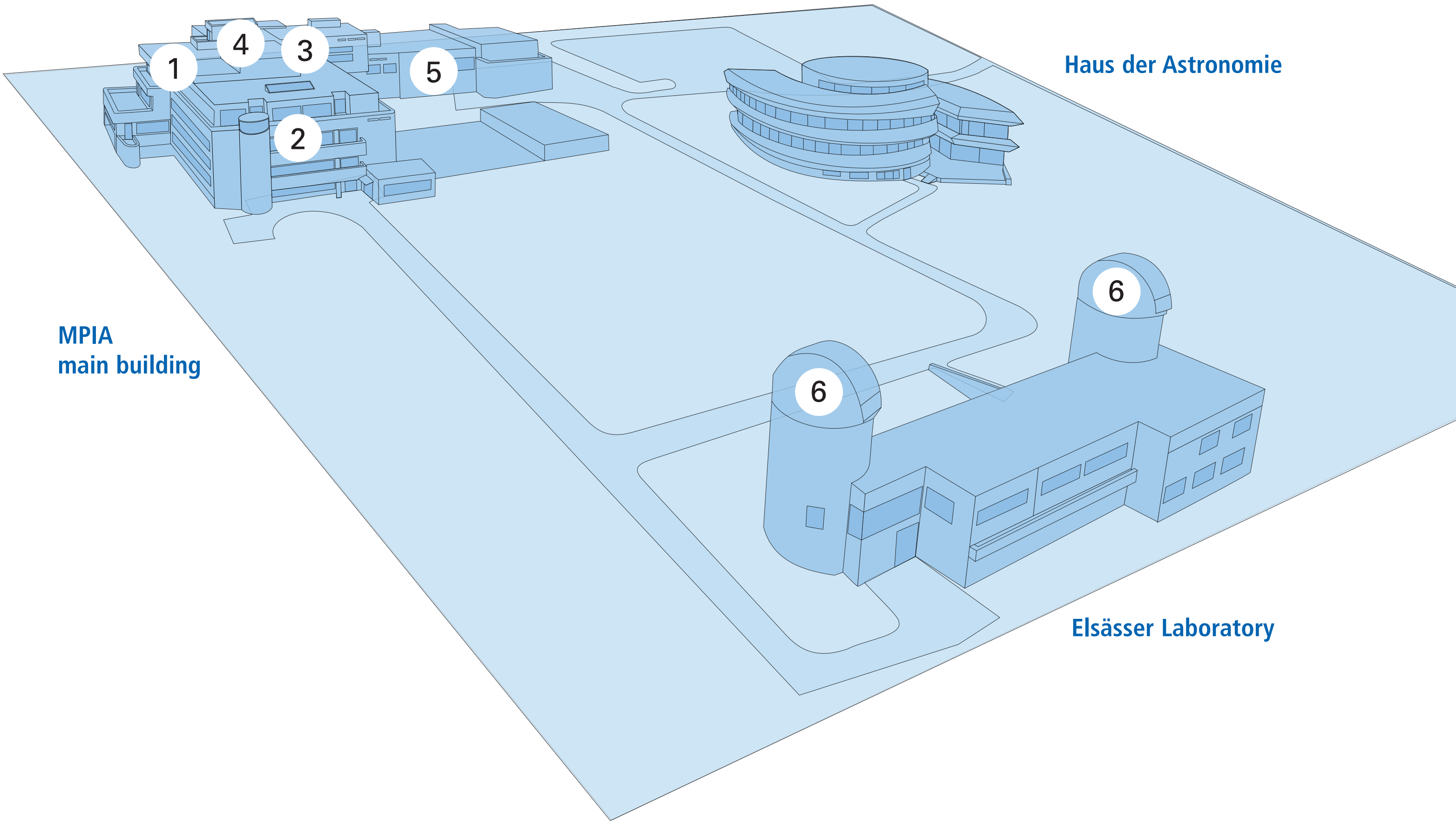
Mattia Sormani, ZAH/ITA
for his publication "A theoretical explanation for the Central Molecular Zone asymmetry" (2018, MNRAS, 475, 2402).

Infrastructure

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

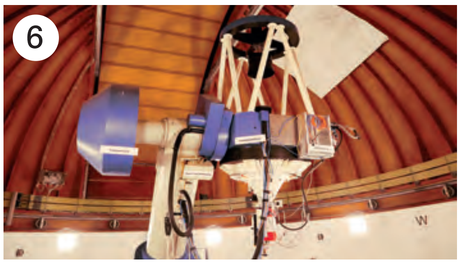
IT infrastructure capable of handling large amounts of data from observations and simulations.

Workshop, construction facilities and lab space, here the new optics laboratory (cf. section III.5).



Two lecture halls and eight seminar/workshop rooms, here the MPIA Seminar Room.

Experimental and assembly facilities including clean rooms for instrumentation.



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

413

employees
keep the institute running. 227 of these are scientists, including 34 junior scientists or long-term visitors and 79 PhD students.

161

million stars
from the Gaia DR2 data release had their temperatures estimated by the MPIA Gaia group.

9

independent research groups
are part of our institute: three Max Planck Research Groups, one group funded by the Alexander von Humboldt Foundation and five European Research Groups.

0.00001

arcseconds
was the astrometric accuracy of observations of the quasar 3C 273 with the GRAVITY instrument, parts of which were constructed at MPIA.

1083

media news items
in print and online covered results presented in MPIA press releases.

700

hours of observations
with ALMA were undertaken for the PHANGS project of MPIA's Eva Schinnerer.

MPIA in Numbers 2018

II. Research: Departments, Collaborations, Highlights

Credit: Illustris Simulation

II.1 Departments

The Planet and Star Formation (PSF) Department

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 – giant molecular hydrogen clouds enriched with dust particles and a large variety of chemical species with masses many thousands of times that of the Sun. 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 is scheduled for launch in 2021. 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 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? 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.

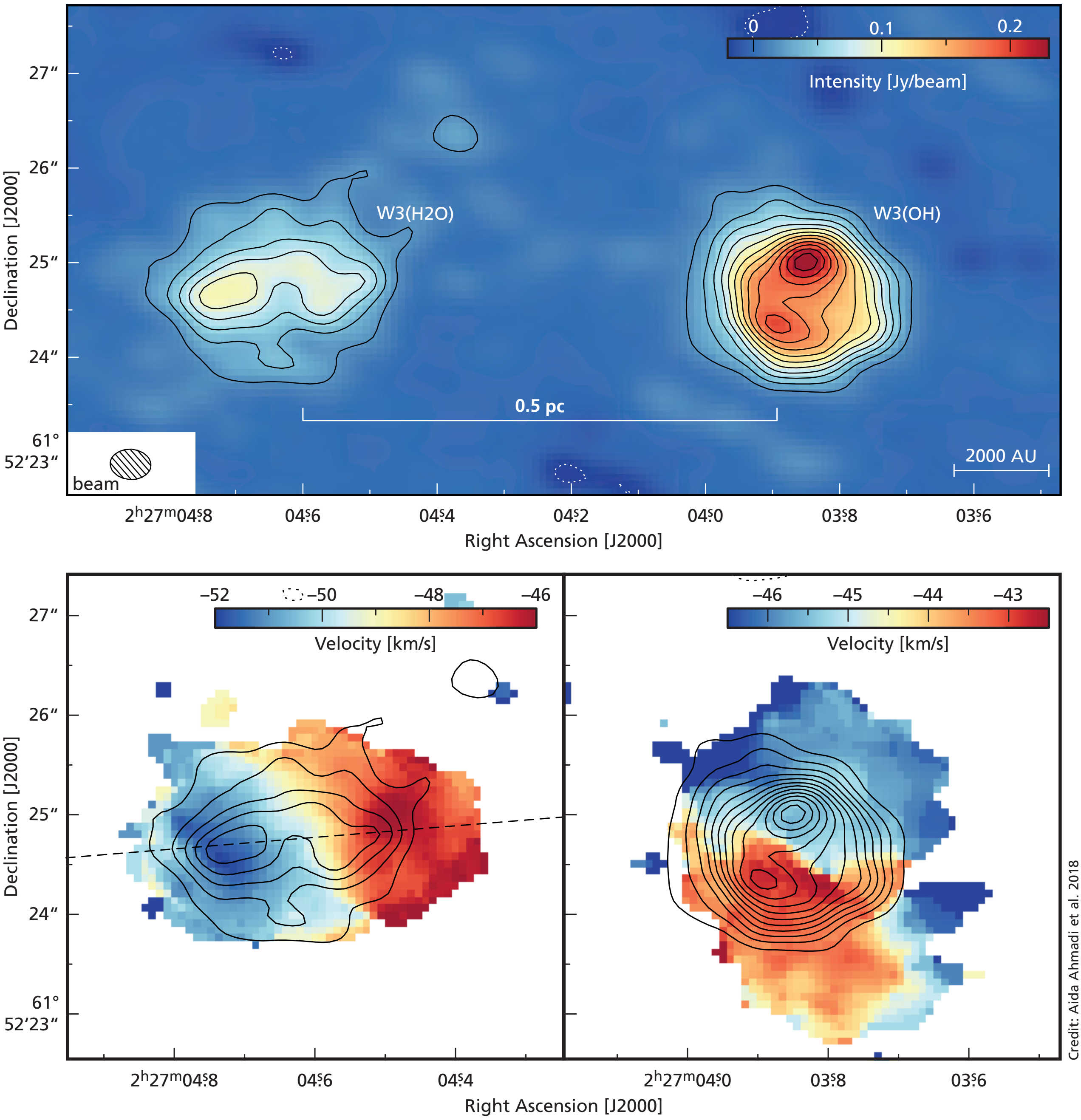
In general, collapsing clouds will fragment to form binary stars or multiple systems. At the high end of the mass scale, the formation of very massive stars takes place in clusters, which makes for exceedingly complex star formation environments. The rapid evolution of massive protostars and the associated 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? 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.

Fig. II.1.1: Millimeter continuum and spectral line data toward the famous high-mass star-forming region W3H2O/OH. The top panel shows the continuum image of the combined field, while the bottom images present in color the first moment maps (intensity-weighted peak velocities) of CH_3CN toward both regions showing the rotation properties. The contours are the same as in the top panel. Such data can be used to characterize the way in which molecular clouds fragment to form numerous stars in short order, including high-mass stars.



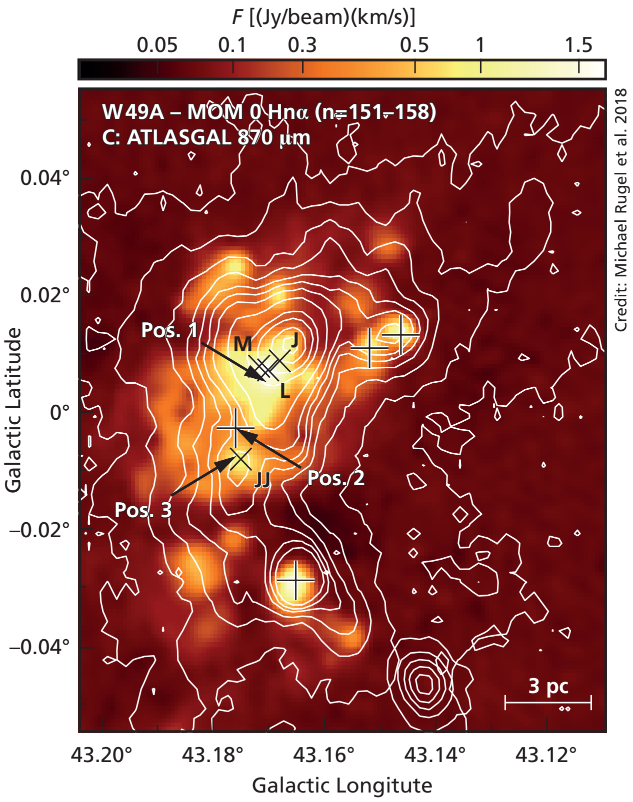


Fig. II.1.2: Radio recombination line (RRL) emission from one of the most luminous HII regions in the Milky Way, W49. The color scale shows the RRL emission, while the contours outline the 870 µm dust emission. Studies of such lines provide valuable clues as to how energy from massive young stars in star formation regions alters the conditions for subsequent episodes of star formation.

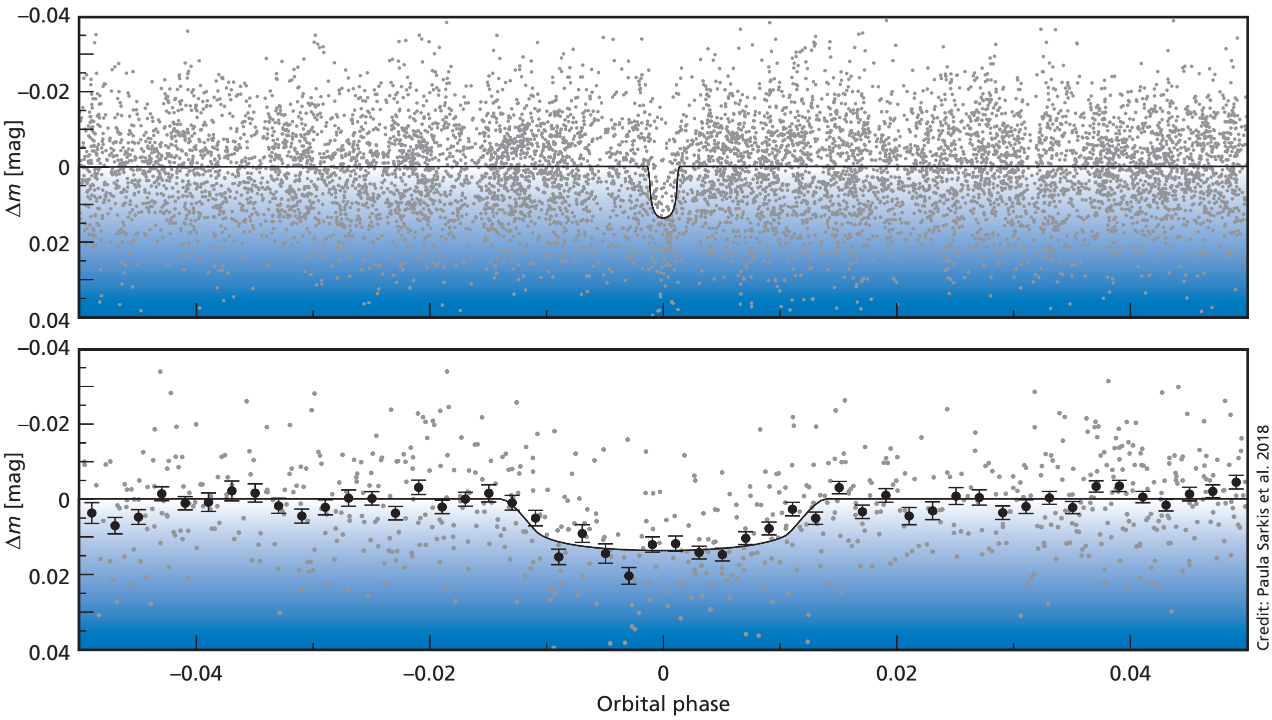
Due to the basic laws of fluid dynamics – namely the conservation of angular momentum – the accretion of matter onto the central protostar happens predominantly via a circumstellar disk. Disks around the low-mass T Tauri stars and the intermediate-mass Herbig Ae/Be-stars are natural birthplaces for planetary systems.

While the protostar 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 can provide insights into both the formation of our own Solar System and the diversity of planetary systems in general.

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 depart-

Fig. II.1.3: The discovery light curve of the exoplanets of HATS-59, phase-folded with a period of 5.42 days. The lower panel shows the central zoom where the filled black points show the light curve binned in phase. With exoplanets HATS-59b, c, this is the first multi-planetary system discovered with the HAT-South network.



ment 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 and protoplanetary disks for the James Webb Space Telescope (JWST), the designated successor of the Hubble Space Telescope. The JWST is scheduled for launch in 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, recently begun instrumentation project, we are looking towards the largest ground-based telescope yet: The PSF department will provide the camera system and part of the adaptive optics system for METIS, the mid-infrared instrument for the Extremely Large Telescope, a 39 meter telescope currently under construction in Chile.

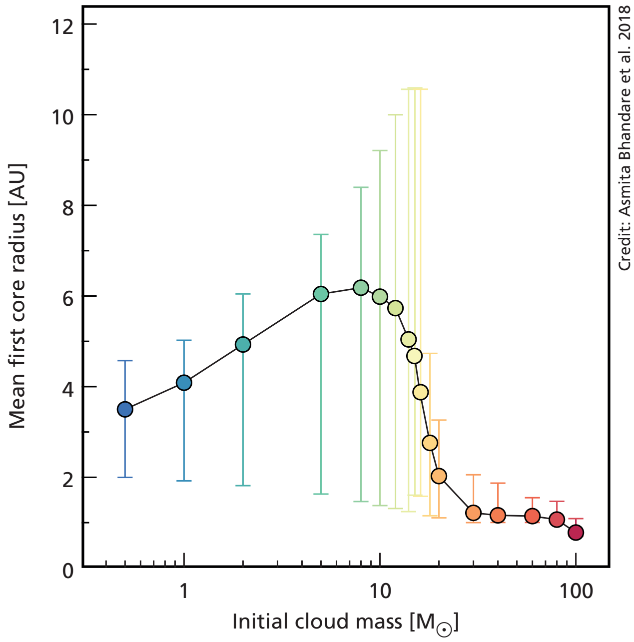


Fig. II.1.4: When parts of a molecular cloud collapse in the earliest phases of star formation, a "first [hydrodynamic] core" is formed, bringing the collapse to an intermediate stop. The diagram shows simulation results for the evolution and properties of such first cores over a broad range of stellar masses – for light stars as well as for highly massive ones. The figure shows the radius of the first core plotted versus the initial cloud mass.

Planet formation and the search for exoplanets

The detection of the first extrasolar planets around Sun-like stars in 1995 signalled a new era for the study of planet formation in protoplanetary disks. Suddenly, instead of a single example of a planetary system – our own Solar System – astronomers were able to examine, compare and contrast hundreds, more recently even thousands of such systems.

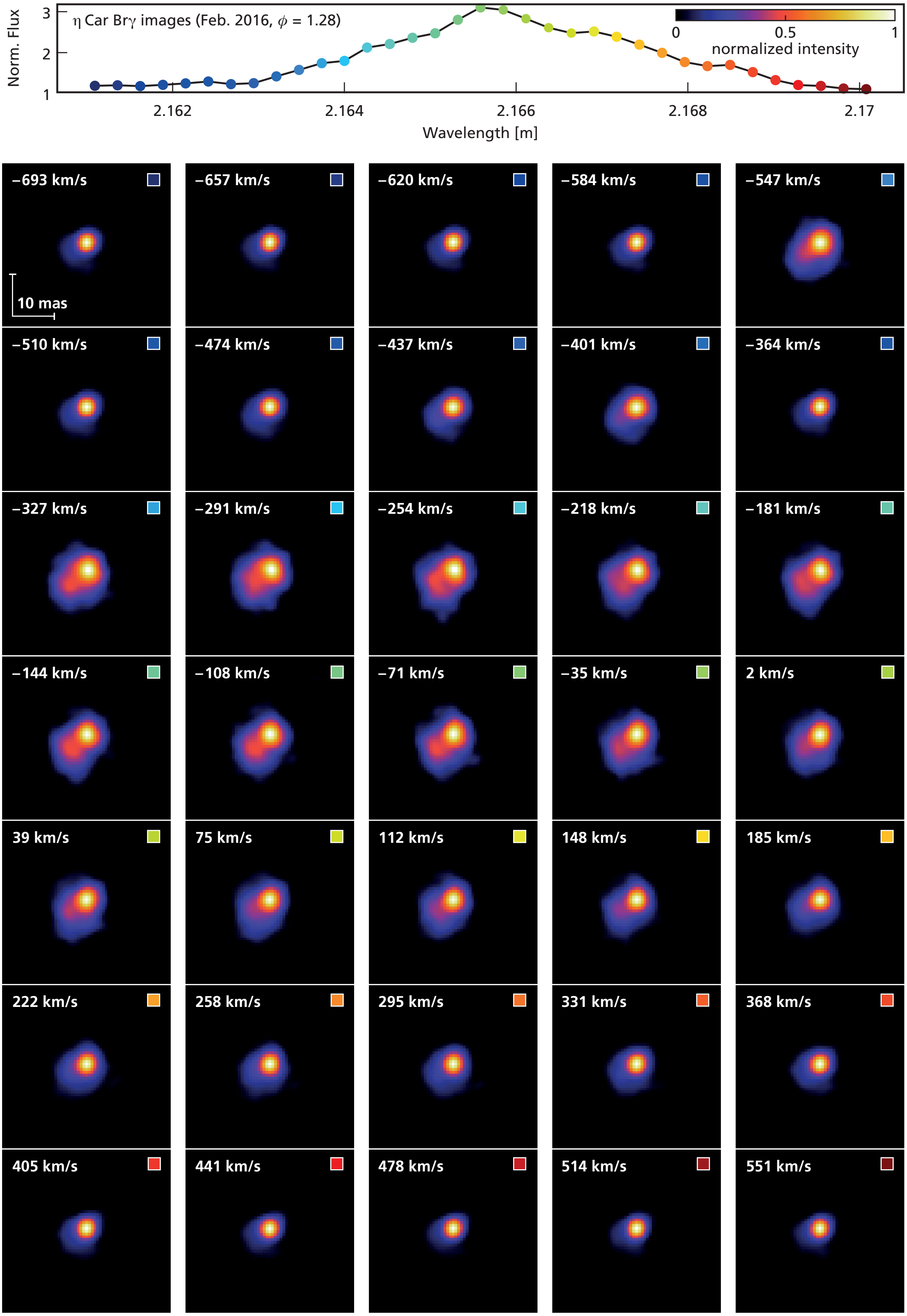
PSF astronomers are heavily involved in observing programs to search for extrasolar planets through direct imaging, the transit technique and radial velocity observations of objects discovered with the Kepler Space Telescope. The HATSouth transit network, with its three stations in Australia, Chile and Namibia, is currently returning a wealth of new discoveries, while the K2 mission extension of the Kepler observatory is enabling us to detect super-Earths around relatively bright stars. Moreover, the new 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 has started to unravel the statistics of low-mass planets around these red stars, and the first planet discoveries could now be made.

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 is also a key member of the LBT LEECH planet search program and has initiated a large survey for young planets with the adaptive-optics instrument NACO.

Furthermore, two instruments for ESO's Very Large Telescope Interferometer, GRAVITY and MATISSE, to both of which have the PSF department has greatly contributed – have been built or are in their final stage of construction. GRAVITY has already produced amazing scientific results in various fields from the Galactic Center to stellar multiplicities, while the first light and early commissioning of MATISSE was in 2018, with real science expected to be possible in 2019. Both instruments will allow us to study the cradles of planets – protoplanetary disks – with unprecedented spatial resolution, complementing our observations with the IRAM and ALMA (sub)millimeter interferometers.

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 thus 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



Credit: GRAVITY Collaboration, Joel Sanchez-Bermudez et al. 2018 during star and planet formation. Additional topics of our theory group are the formation of low- and high-mass stars as well as star formation on galactic scales.

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. 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.

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.

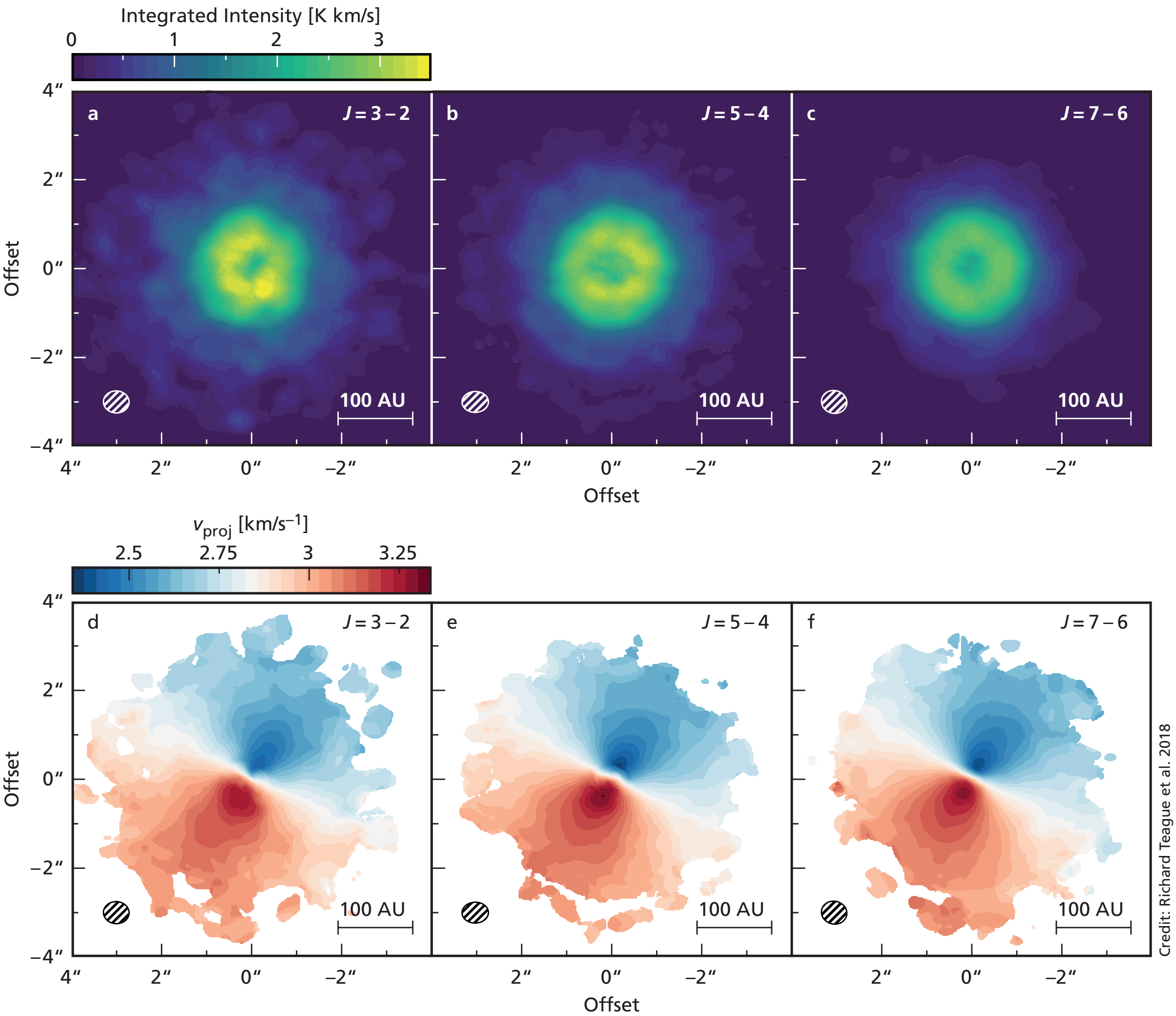
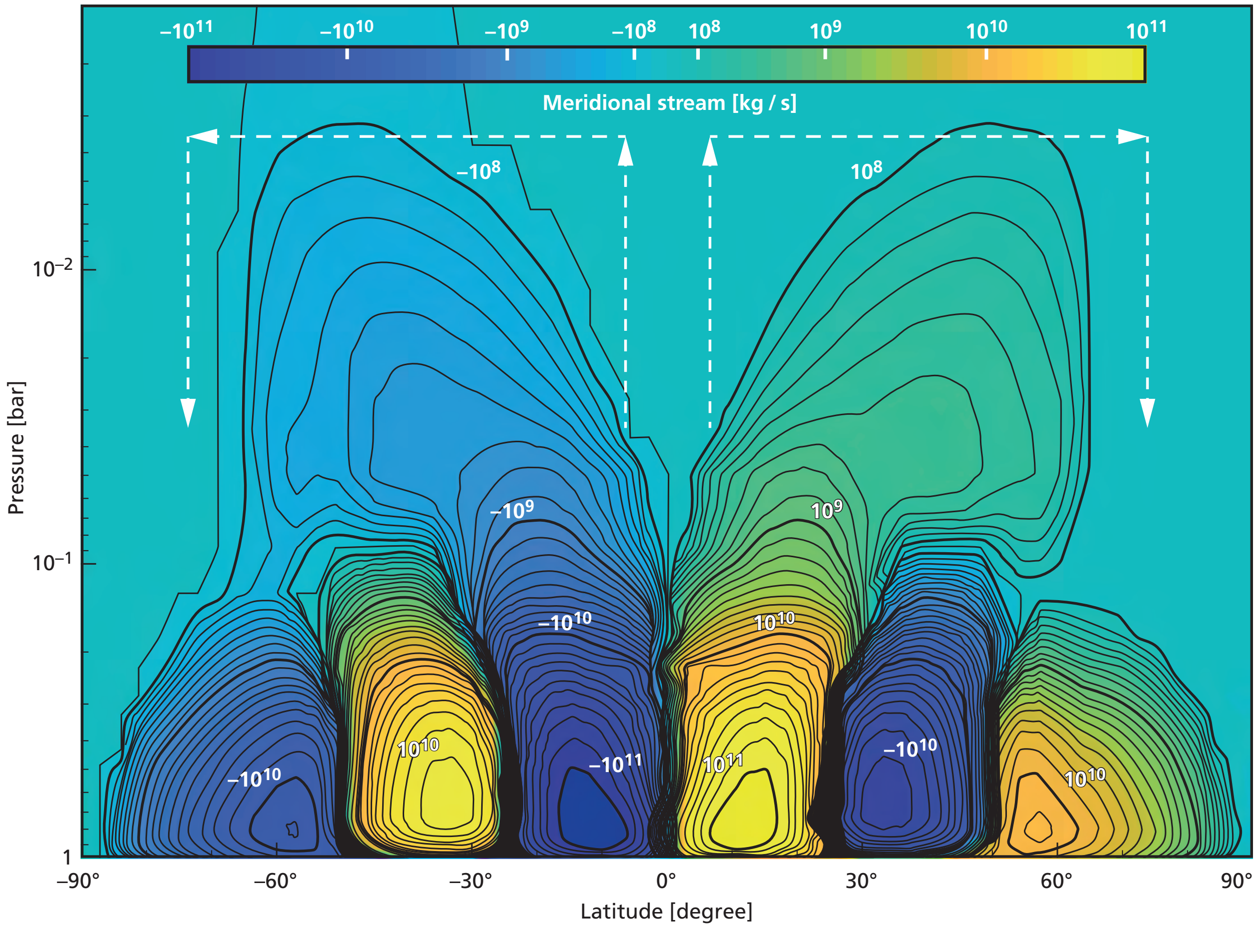


Fig. II.1.6: ALMA multi line observations in various CS transitions of the protoplanetary disk TW Hydrae. The top panel shows the integrated emission maps of the labeled transitions, and the bottom panels show the corresponding first moment maps (intensity-weighted peak velocities) outlining the rotational structure of the disk by showing which regions are moving towards us or away from us, and how fast. Measurements like this yield information about the prevalence of turbulence within the disk and also help to estimate the disk mass.

Fig. II.1.5: *Left:* Carinae is a blue variable star, probably a binary star with one very massive component of around 100 solar masses, in a late stage of stellar evolution. With the help of this GRAVITY interferometric channel map in the Bracket gamma line, researchers have attempted to refine their models of this interesting stellar system. The top panel shows the spectrum, while the bottom panels present the images obtained at the various marked wavelengths/velocities.



Credit: Ludmila Carone et al. 2018

Fig. II.1.7: Several known exoplanets that are similar in size to the Earth are tidally locked to their host star, with one side of the planet permanently facing the star. This locking influences the dynamics of the planetary atmosphere, including the formation and prevalence of molecules in the atmosphere that could, in the future, be used to determine whether there is life on an exoplanet. That is why simulations of such atmospheres are highly important. The image shows an example: the meridional stream function for an Earth-like setup to model stratospheric circulation in the atmosphere.

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.

Linking the cosmos with laboratories of another kind altogether, namely those of our colleagues in macromolecular chemistry, biogeochemistry and the life sciences, 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.

II.2 Departments

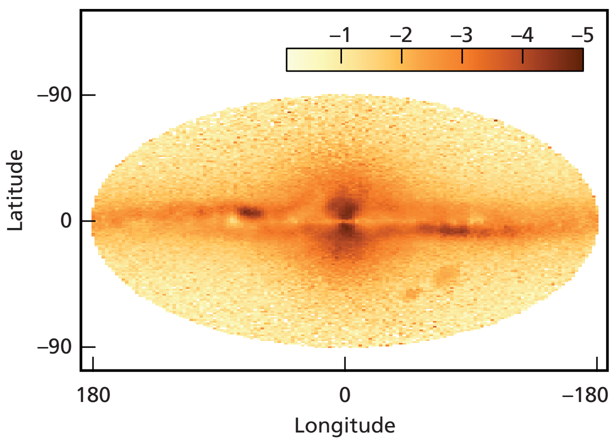
Galaxies in their Cosmological Context – The GC Department

Director: Prof. Dr. Hans-Walter Rix

How the Universe became interesting

Shortly after the Big Bang, the Universe was almost perfectly homogeneous and simple, that is: both elegant and boring. In stark contrast, the present cosmos exhibits a rich hierarchy of structures spanning a wide range of physical scales: from the filamentary distribution of galaxies known as the cosmic web down to 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 all the large-scale structure appears to be driven by gravitational instabilities – by the ubiquitous influence of gravity, of matter pulling itself together, large structures collapsing and contracting. On the scales of galaxies, a plethora of other physical effects come into play.

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 concentrations arise 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 (at least in physical scale) of the overall hierarchical structure of the cosmos.



Credit: Coryn Bailer-Jones et al. 2018, Astronomical Journal 156, 58.

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

Emerging order in the realm of galaxies

Galaxies exist over a vast range of physical scales: they vary by many orders of magnitude in their stellar masses, in their rate of producing new stars, the mass of the black holes at their very centers, and their sheer physical size.

Yet, as Edwin Hubble realized 80 years ago, these "island universes" are not as varied in their appearance and structure as the laws of physics would allow. Observations, particularly those made over the last 15 years, have confirmed this in ever greater detail: only a small fraction of the possible combinations of galaxies' characteristic quan-

Fig. II.2.1: Geometric distances to astronomical sources can be obtained from parallaxes. However, the simple relation of inverting a parallax to get a distance only works if the parallax has an arbitrarily small uncertainty. This is rarely the case, even for the exquisitely accurate parallaxes in the second Gaia data release. A team at MPIA has inferred distances to over one billion sources in our Galaxy using a combination of these parallaxes and a model of the distribution of stars in our Galaxy. This map of the entire sky shows the mean distance to stars in our Galaxy inferred by this approach (Mollweide equal-area projection in Galactic coordinates). The bulge and plane of the Galaxy are clearly visible as regions in which stars are, on average, further away from the Sun. Even though we can observe to much larger distances at high Galactic latitudes due to the lack of obscuring dust away from the disk, the average distances at low latitudes are nonetheless larger. (This, in turn, is due to the much higher density of stars in the Galactic disk.) The large and small Magellanic clouds are visible, but their distances are significantly underestimated. This is because the Gaia parallaxes alone are not precise enough to estimate distances to invidiual stars in these satellite galaxies at all, so the distance estimates are dominated by the prior Galactic model (which does not include external galaxies).

tities (stellar masses and ages, size, central black hole and more) are actually realized in the Universe. Virtually all physical properties strongly correlate with all other properties: massive galaxies are large; massive galaxies contain virtually no young stars; the central black hole mass is proportional to the galaxy's spherical distribution of stars ("bulge") in spite of the vast difference in size between the two structures (a factor of roughly ten million). While spiral galaxies are the most common kind of galaxy, none of the most massive galactic specimens are of this type.

All this means that the "realm of galaxies", to use Hubble's expression, exhibits a high degree of order. How did this order develop from the random mass fluctuations that amounted to large-scale structure shortly after the Big Bang? That is the fundamental question of galaxy formation and a central issue in cosmology.

There are three broad lines of explanation for the limited variety in the zoo of galaxies. Either, observed galaxies represent the only configurations that are dynamically stable over long times. If each galaxy spends a long time in a stable state, and a very brief time only in a transitional state, then with astronomical observations at an essentially random moment in cosmic time (namely now), we are unlikely to catch more than a few (if any) galaxies in transition.

Alternatively, it is possible that the initial conditions of our Universe only permitted the formation of the galaxies we see. Finally, it is conceivable that galaxy formation is a highly self-regulating process that, regardless of initial conditions, can only result in a very limited set of outcomes – namely those combinations of properties that we actually observe.

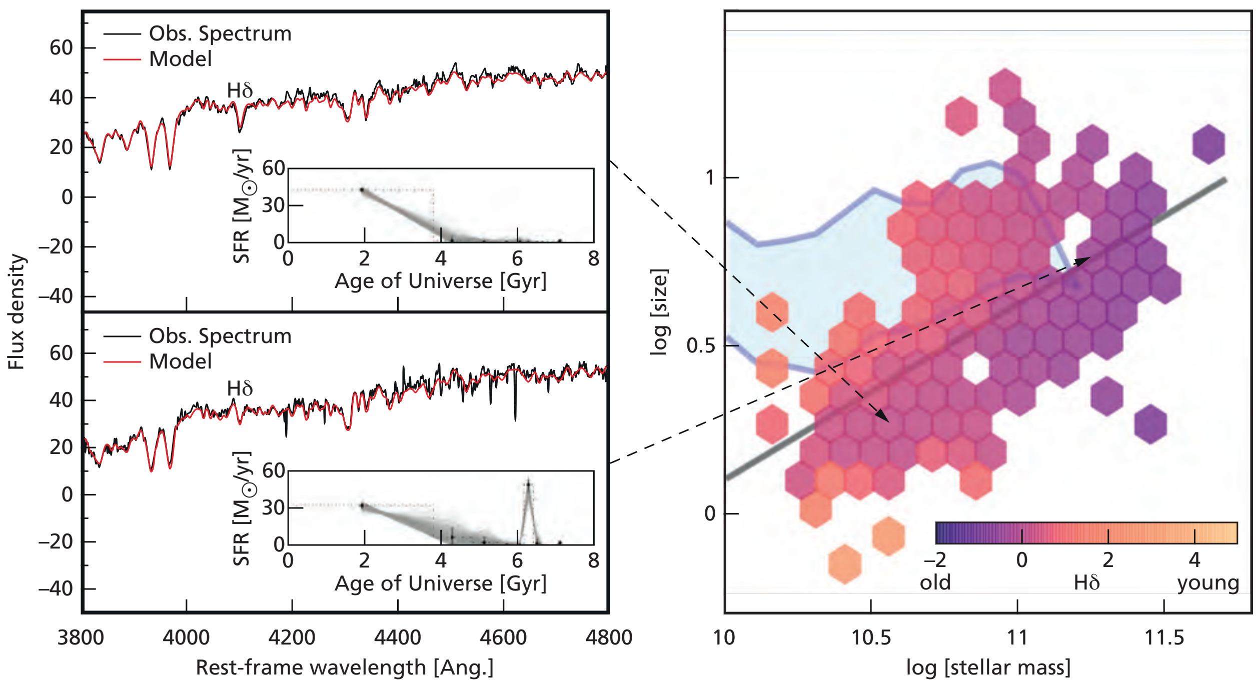
Current research suggests that all three aspects may play a role.

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

Fig. II.2.2: LEGA-C is a Public Spectroscopic Survey at ESO's VLT collecting more than 3000 high-quality spectra of galaxies at redshift $z \sim 1$ aimed at inferring the stellar content and dynamical structure of galaxies when the Universe was half its present age. *Left:* two LEGA-C example spectra of galaxies and their reconstructed star-formation histories inferred from modelling the spectra. Both galaxies are old, but the example at the top had a recent secondary burst of star formation. This contrast is traced by the different strength of, for example, the Balmer absorption line H_δ. *Right:* Star-formation histories (here using by H_δ as proxy for a sample of several 100 galaxies) correlate in a complex manner with other galaxy parameters – here, total stellar mass and size. Generally, massive galaxies have older stellar populations, and for less massive galaxies the age correlates with size: both the largest and the smallest galaxies tend to have young stars. This qualitatively new information of high-redshift galaxies provides strong additional constraints on galaxy formation models.



Credit: Priscilla Chauke et al. 2018 *(left)* / Po-Feng Wu et al. 2018 *(right)* just as important: how does gas get reheated and possibly ejected from galaxies, either by the intense radiation of luminous young stars, by supernova explosions, or by the presence of an active central black hole?

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

The Milky Way, a model organism for understanding galaxies

Our own galaxy is very average, 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 a rapidly evolving and exciting field.

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?

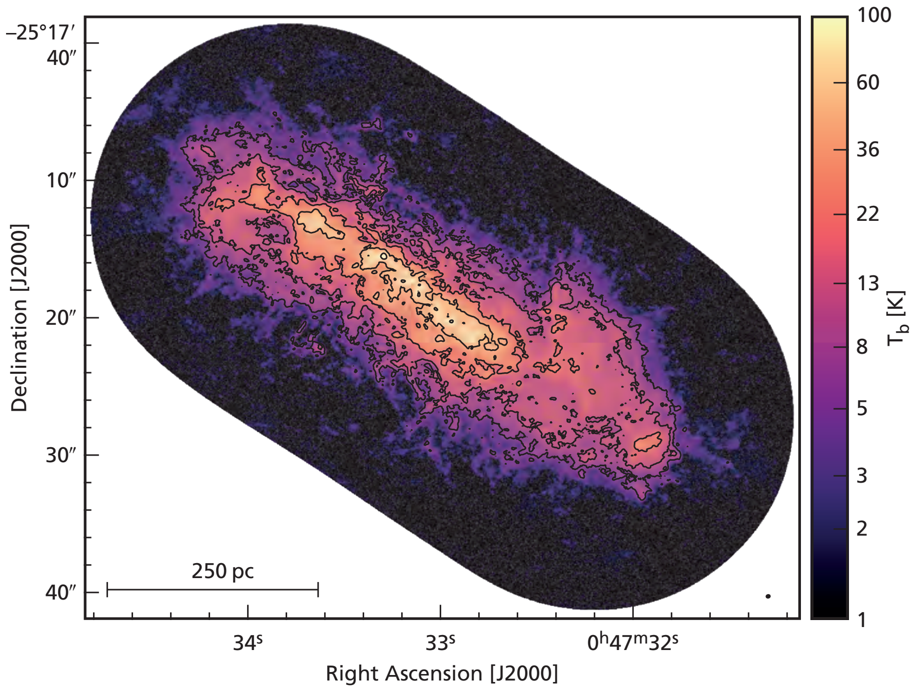


Fig. II.2.3: The distribution of carbon monoxide (CO) in the center of the nearby starburst galaxy NGC 253: The CO molecule is a good tracer of the molecular interstellar medium (ISM) which is the fuel for star formation. In its center, NGC 253 is actively forming stars, called a starburst. As the collapse of gas clouds into stars happens on small scales, high spatial resolution is needed to study the ISM that will eventually be converted into stars and its interaction with the already existing stars. This image was observed with the Atacama Millimeter/Submillimeter array (ALMA) in Chile which can detect the emission emitted by the CO molecules with high resolution and sensitivity. With ALMA, we can achieve an unprecedented resolution of 2.5 pc (shown by the small black ellipse in the lower right corner) over the 800 pc field-of-view. For the first time, these data resolve the complex interplay between star formation and ISM that shapes the complex structures seen in this image.

Credit: Nico Krieger et al. 2019, ApJ, submitted

Credit: Annalisa Pillepich, MPIA et al. 2018

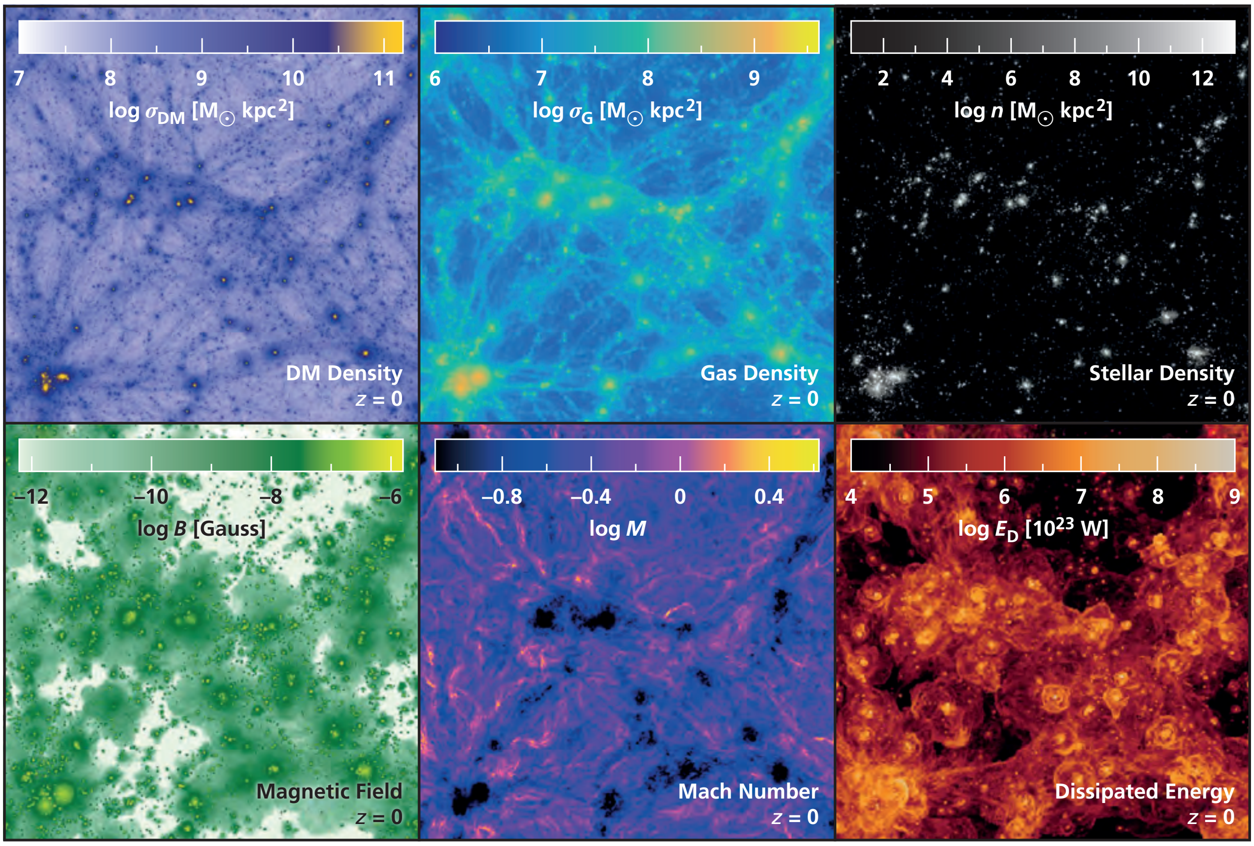


Fig. II.2.4: Cosmic gas on large cosmological scales from the IllustrisTNG simulations. The maps depict, from top left clockwise, the projected mass density of hydrogen, gas temperature, gas metallicity, the energy dissipated in cosmic shocks due to gravitational collapse or fast gas outflows from galaxies, the average Mach numbers of such shocks, and the strength of the cosmic magnetic fields. Galaxies and their stars form at the center of dense haloes and massive haloes of matter.

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 questions of when can be addressed by looking at distant galaxies, which we see at an earlier epoch – because the speed of light is not infinite. The how can be addressed by mapping the gas (the fuel for star formation) and the star formation itself in great detail in closer galaxies.

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

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

From observations to simulations

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

On the other hand, 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, 9 billion years to reach us, our present observations show us that galaxy as it was 9 billion years ago, affording us a glimpse into the distant past.

Finally, we develop physical models and progressively improve both them and our understanding of galaxy formation by testing their outcome against observations. 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.

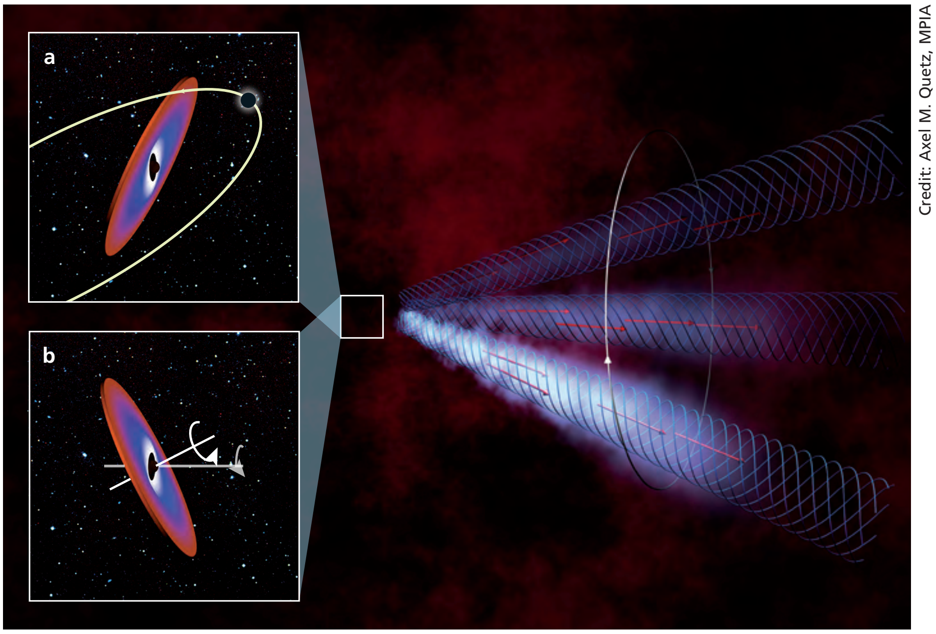


Fig. II.2.5: Zoom into the heart of the galaxy OJ 287 (artist's impression) with its active, supermassive black hole. An international research team led by Silke Britzen of the Max Planck Institute for Radio Astronomy, which includes MPIA's Christian Fendt, has discovered that the active nucleus of this galaxy generates a jet that staggers like a spinning top on a timescale of about 22 years. This explains the fluctuation of the radiation of OJ 287. The precession could either be caused by a binary black hole (*Inset a*) or by a mis-aligned accretion disk (*Inset b*).

Comprehensive studies of galaxy evolution also require observations across the whole of the electromagnetic spectrum from X-rays to radio wavelengths.

The theoretical models, on the other hand, must be able to produce increasingly realistic populations of galaxies across an ever wider spectrum of properties such as masses, environments, evolutionary stages, and cosmic epochs. The models developed and analyzed at MPIA follow the co-evolution of dark matter, stars, cosmic gas, magnetic fields, 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.

Collaborations and initiatives

MPIA is leading a number of major, global observing programs to tackle these questions. These range from deep fields with ALMA to find dense gas at high redshifts to large programs at the VLT and Keck to study the intergalactic medium, and a VLT legacy survey to study the physics of high-redshift galaxies.

But we are also leading large initiatives using the VLA of the National Radio Astronomy Observatory in the US state of New Mexico, and IRAM's NOEMA in the French Alps, to map gas in nearby galaxies and the most distant quasars. Furthermore, we have taken on a central role in shaping the next generation of surveys for black hole and galaxy formation, and for the formation of our Milky Way. Extensive spectroscopic surveys of nearby galaxies map their stars' kinematics to reveal their dynamical structure and the nature of their central black holes.

MPIA has had a leading role in making 3D maps of the Milky Way, in particular with Gaia. Finally, MPIA is leading the near-infrared photometry effort on ESA's Euclid mission, which will elucidate the most puzzling aspects of physics in the cosmos: the nature of dark energy.

II.3 Internatioinal Networking

Scientific Initiatives

Science is a cooperative venture, and large-scale projects are usually tackled by more than one institute: in larger consortia or as a cooperative project between selected institutes. MPIA is an integral part of the international astronomy landscape and takes part in a number of key initiatives.

Sloan Digital Sky Survey IV and V

MPIA is a member of the Sloan Digital Sky Survey IV (SDSS), a spectroscopic survey using the Sloan Foundation 2.5 meter telescope at Apache Point Observatory, and a full institutional partner in SDSS-V, which provide level, all-sky, multi-epoch spectroscopy of stars and black holes. With the Project Scientist and a Survey scientist at MPIA, the institute plays a leading role in the international SDSS-V consortium.

LSST: the Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope will take rapid, deep sky imaging to a new level in 2022. The MPIA has joined the consortium, and is now strengthening its participation, as the combination of the LSST data and data from the Euclid space mission promise a scientific boon.

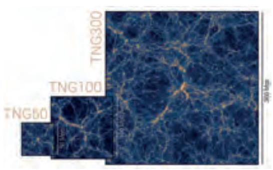
Gaia

Within the Data Processing and Analysis Consortium of ESA's Gaia mission, an MPIA team leads the effort for classifying sources and determining stellar parameters from Gaia data, a major contribution to the mission's second data release. These scientists also use Gaia data to investigate local stellar kinematics, the distribution of dust in the Milky Way, and the properties of star clusters and stellar streams.

LEGA-C

The LEGA-C survey at ESO's VLT/VIMOS instrument collects >3000 high-quality galaxy spectra at $z \sim 1$. The aim is to study the evolution of galaxies, in particular their star formation history, to put strong constraints on the latest generation of galaxy formation models. MPIA and Ghent University (Belgium) are the main partners and the research effort is primarily funded through an ERC Consolidator Grant.

IIllustrisTNG



The IllustrisTNG project (www.tng-project.org) is a series of simulations including gravity and magnetohydrodynamics, which follow the evolution of thousands of galaxies in different environments, allowing insight on a wide range of scales from the classical dwarf galaxies of the Milky Way to the cosmic web. The collaboration includes astrophysicists in Heidelberg, Munich, New York City and Boston.

Collaborative Research Center 881: The Milky Way System

MPIA is part of the Collaborative Research Center 881 at the University of Heidelberg, which is funded by the German Science Foundation (DFG). SFB 881 examines various properties of our home galaxy to obtain a better understanding of its structure and evolution, as well as of the evolution of galaxies in general.

Heidelberg Initiative for the Origins of Life

The Heidelberg Initiative for the Origins of Life brings together researchers from astrophysics, geosciences, macromolecular chemistry, statistical physics and life sciences from MPIA, the Max Planck Institute for Nuclear Physics, the Heidelberg Institute for Theoretical Studies, and the University of Heidelberg in order to further our understanding of the origins of life in the Universe.

DFG Priority Programs

MPIA takes part in the German Science Foundation's SPP 1573, a priority programme that is dedicated to research on the interstellar medium: the dilute mixture of charged particles, atoms, molecules and dust grains filling interstellar space. PSF scientists actively contribute to the DFG Priority Program SPP 1833 "Building a Habitable Earth" and the SPP 1992 Priority Program "Exploring the Diversity of Extrasolar Planets". MPIA scientist are PIs of the research projects in the DFG Research Unit 2544 "Blue Planets and Red Stars. Exploitation of the Carmenes Survey" and the DFG Research Unit 2285 "Debris Disks in Planetary Systems".

International Max Planck Research School "Astronomy and Cosmic Physics"

MPIA is one of the founders of the International Max Planck Research School "Astronomy and Cosmic Physics" at the University of Heidelberg, which provides an internationally competitive graduate program to German and international students (see section IV.1).

HAT-South

This collaboration between MPIA, Princeton University, the Australian National University and the Pontificia Universidad Catolica de Chile utilizes a network of six identical, fully automated wide-field telescopes in Namibia, Australia, and Chile to search for transiting exoplanets. The survey has already identified more than 30 new exoplanets, including some particularly interesting objects.

CARMENES-Radial Velocity Survey

MPIA is involved in a long-term search for extrasolar planets around M stars, using the high-resolution spectrograph CARMENES at the Calar Alto Observatory. The project involves several German and Spanish institutes. The CARMENES spectrograph has a visible-light as well as a near-infrared arm.

SHINE and ISPY: Direct exoplanet search and characterization

With the SHINE Survey, MPIA and other institutes of the SPHERE consortium are looking for exoplanets, using images taken with extreme adaptive optics at ESO's VLT and characterizing the atmospheres of known directly imaged planets. In parallel, and in cooperation with Landessternwarte Heidelberg and the Geneva Observatory, MPIA is conducting an L band survey of exoplanets (ISPY) using the VLT instrument NACO.

THOR – The HI, OH, Recombination Line Survey of the Milky Way

PSF scientists are leading the large VLA program THOR to study the structure of the interstellar medium and particularly to establish the relation between atomic and molecular gas in our galaxy. This survey is led by MPIA with strong contributions from European and US institutions.

CORE – Fragmentation and disk formation in high-mass star formation

Utilizing the Northern Extended Millimeter Array (NOEMA, formerly known as Plateau de Bure Interferometer), PSF scientists are leading a large program that studies the fragmentation and disk formation processes during the earliest evolutionary stages of the formation of the most massive stars. This survey is led by MPIA with strong contributions from European and US institutions.

PHANGS — Physics at High Angular Resolution in Nearby Galaxies

Using observations from ALMA, VLT/MUSE and the HST, this collaboration aims to understand the interplay of the small-scale physics of gas and star formation with galactic structure and its role in galaxy evolution. The MPIA-led international collaboration brings together observers and theorists from Heidelberg, Europe, Chile, Australia and the US.

ASPECS – ALMA Spectroscopic Survey in the Hubble Ultra Deep Field

This survey of arguably the best-studied extragalactic field in the sky discloses the density of the star-forming medium in galaxies through cosmic times and unveils reservoirs of molecular gas in galaxies up to $z \sim 4$, throwing light on the formation and evolution of galaxies. ASPECS is a large international collaboration led by MPIA, including 40 scientists from 35 institutes in 9 countries.

Additional initiatives with active MPIA involvement are the technological collaboration Frontiers of Interferometry in Germany FrInGe, the Opticon network for institutes involved in planning and building optical and infrared instruments and telescopes, the international consortium Chemistry in Disks (CID) focusing on the chemistry and physics of protoplanetary disks and the exoplanet search LEECH at the Large Binocular Telescope. The first Max Planck Tandem Group in the field of Astronomy in Chile is a cooperation between MPIA and the Institute for Physics and Astronomy (IFA) of the Universidad de Valparaíso, Chile.

II.4 Highlights

Observations link galaxies' central black holes and star formation

Astronomers have found the first direct observational evidence for a long-suspected link between galaxies' central black holes and the rate at which stars form throughout a galaxy's history. To this end, astronomers made use of a survey of black hole masses and reconstructed each galaxy's star formation history from its spectrum. Black hole mass and star formation rate were found to be clearly linked, confirming a connection that had been assumed to exist for a considerable time.

In the center of (almost) every galaxy is a supermassive black hole with the mass of between a few hundred thousand and a few billion times the mass of the Sun. Astronomers have known for decades that there is an unusual connection between those black holes and the stars of the host galaxy. Simulations of cosmic evolution routinely assume that this is due to a link between the mass of the black hole and the rate at which a galaxy forms new stars.

A group of astronomers led by Ignacio Martín-Navarro (University of California Observatories and Max Planck Institute for Astronomy [MPIA], Heidelberg) has found the first observational evidence for a direct correlation between the total mass of a galaxy's central black hole and the galaxy's star formation history.

Credit: ESA / Hubble & NASA

Fig. II.4.1: The galaxy NGC 660 – in this and other galaxies, the rate at which new stars are formed appears to be linked to the evolution of the galaxy's central black hole.

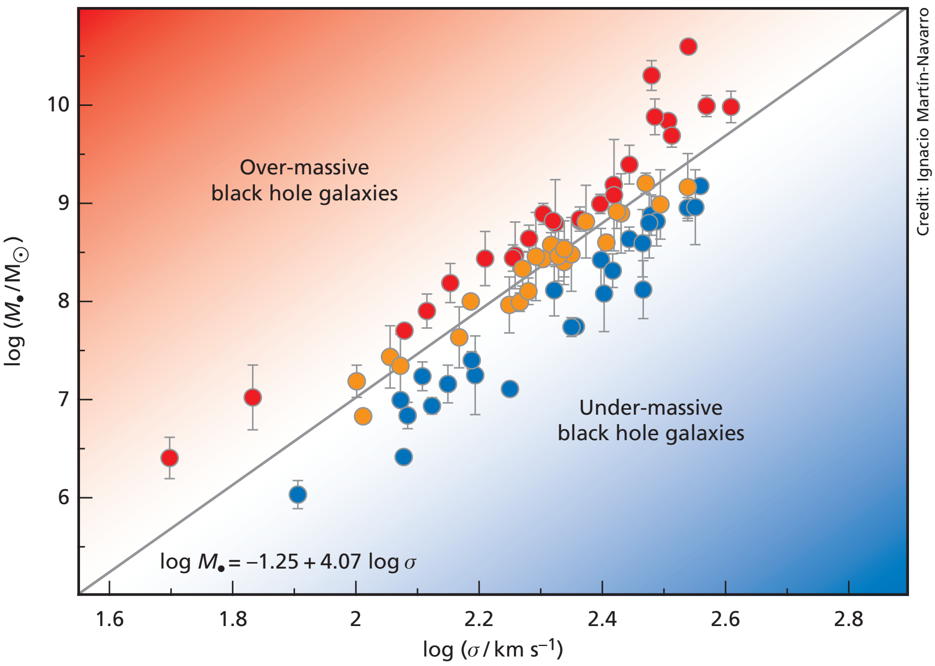


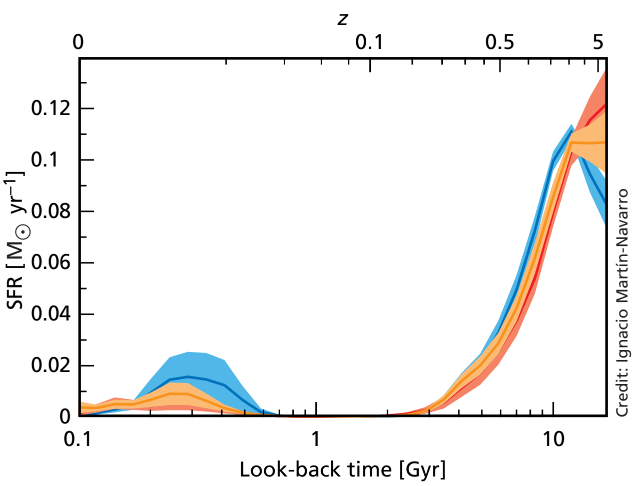
Fig. II.4.2: There is a well-established empirical correlation between the velocity dispersion of the stars and the mass of the central black hole which was applied to the 74 galaxies used in this study. This correlation was used to identify galaxies with black holes that have significantly lower (*blue*) and higher masses (*red*) than the average (*orange*).

Galactic central black holes influence star formation

When this correlation was discovered some 15 years ago, it appeared to be a key property of galaxies – but it also posed a puzzle. What could be the cause of such a correlation? And what could physically link two objects so dissimilar in size as the stellar population, distributed throughout a galaxy, and the black hole at the galaxy's center which, in comparison, is rather tiny?

One possible connection is comparatively straightforward: more massive galaxies can collect larger amounts of gas, producing both more stars and a more massive central black hole.

It has long been thought that there is also a smaller, opposing influence due to growing black holes inhibiting the formation of stars in their vicinity. The basic physics is fairly plausible: When black holes grow by accumulating matter, enormous amounts of energy are released. If that energy is transferred to the gas within and surrounding the galaxy – for instance via radiation, or by the particle jets that frequently accompany infalling matter – then the gas will be less likely to form stars. Gas needs to be cold for individual pockets to collapse, and form stars; energy input will serve to heat up the gas. The effect is more pronounced with larger black holes.



Massive black holes quench star formation

Feedback of this kind has long been included in large-scale simulations of structure formation in the Universe. In fact, it is a necessary component for these simulations to predict realistic star formation rates – without such feedback, the simulated galaxies would have formed far too many stars!

Fig. II.4.3: The history of the star formation rate (SFR) in galaxies with varying black hole masses. Beyond the general trend that the SFR was high in the young galaxies, we can see that around 10 billion years ago galaxies with over-massive black holes (*red*) produced stars at a lower rate than those with under-massive black holes (*blue*).

But observational data directly linking star formation to black hole properties was missing – until now. When Martín-Navarro and his colleagues set out to investigate the issue, they made use of data from the Hobby-Eberle Telescope Massive Galaxy Survey, a systematic study conducted by former MPIA scientist Remco van den Bosch. For 74 of the galaxies surveyed, there exist direct mass measurements of the central black hole (see Fig. II.4.2).

Younger and older stars leave different traces in the spectrum of a galaxy's light. In this way, astronomers were able to reconstruct the star formation histories of their target galaxies for the past 12.5 billion years. The results clearly show the dampening influence of the black hole mass on the star formation rate (see Fig. II.4.3). There is still a clear correlation between black hole mass and stellar mass in these galaxies. However, in those galaxies where the stellar mass is slightly smaller than expected, given their central black hole mass, star formation rates in the galaxy are in turn also reduced; for galaxies with larger-than-expected stellar mass, star formation rates are higher.

Contemporary and historical star formation are consistent

In fact, that connection appears to be closer than the correlation between a galaxy's central black hole mass and its stellar mass, and independent of additional parameters such as the galaxy's shape or stellar density.

Moreover, the correlation extends far into the past. Not only are those galaxies with more massive central black holes than expected now producing fewer stars. They have consistently been producing stars at a comparatively low rate for the past 12.5 billion years. This is strong evidence of a direct, long-term connection between star-forming activity and the central black hole.

Now, the ball is firmly in the court of the theoreticians who will need to explain the physical mechanisms behind the link – and who will be able to test their explanations using the observational data Martín-Navarro and his colleagues have provided.

Ignacio Martín-Navarro
(also University of California Observatories),
Glenn van de Ven
(also ESO)

in collaboration with

Jean P. Brodie (University of California Observatories),
Aaron J. Romanowski (University of California Observatories and San José State University),
and Tomás Ruiz-Lara
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I. Martín-Navarro et al. 2018, "Black-hole regulated star formation in massive galaxies" in Nature, Vol. 553, p. 307.
DOI: 10.1038/nature24999

II.5 Highlights

Library of galaxy histories reconstructed from motions of stars

The motions of stars in a galaxy are like a history book, yielding information about how the galaxy has grown over time. A team of astronomers led by scientists of the Max Planck Institute for Astronomy have put together a library of such galaxy history books. Covering a total of 300 galaxies, their data showcases the diversity of the various ways different galaxies came into being over the past billions of years. This is the first large-scale library of galactic histories and it is a particularly important tool for astronomers running simulations of cosmic structure formation, since those simulations can now be checked against a large set of observations.

For stars in galaxies, there are two kinds of basic motion. Some orbit the center of the galaxy in a regular way – just like our Sun, and billions of other stars, orbit the center of our home galaxy, the Milky Way, in an ordered disk. Other stars have randomly oriented, elongated orbits

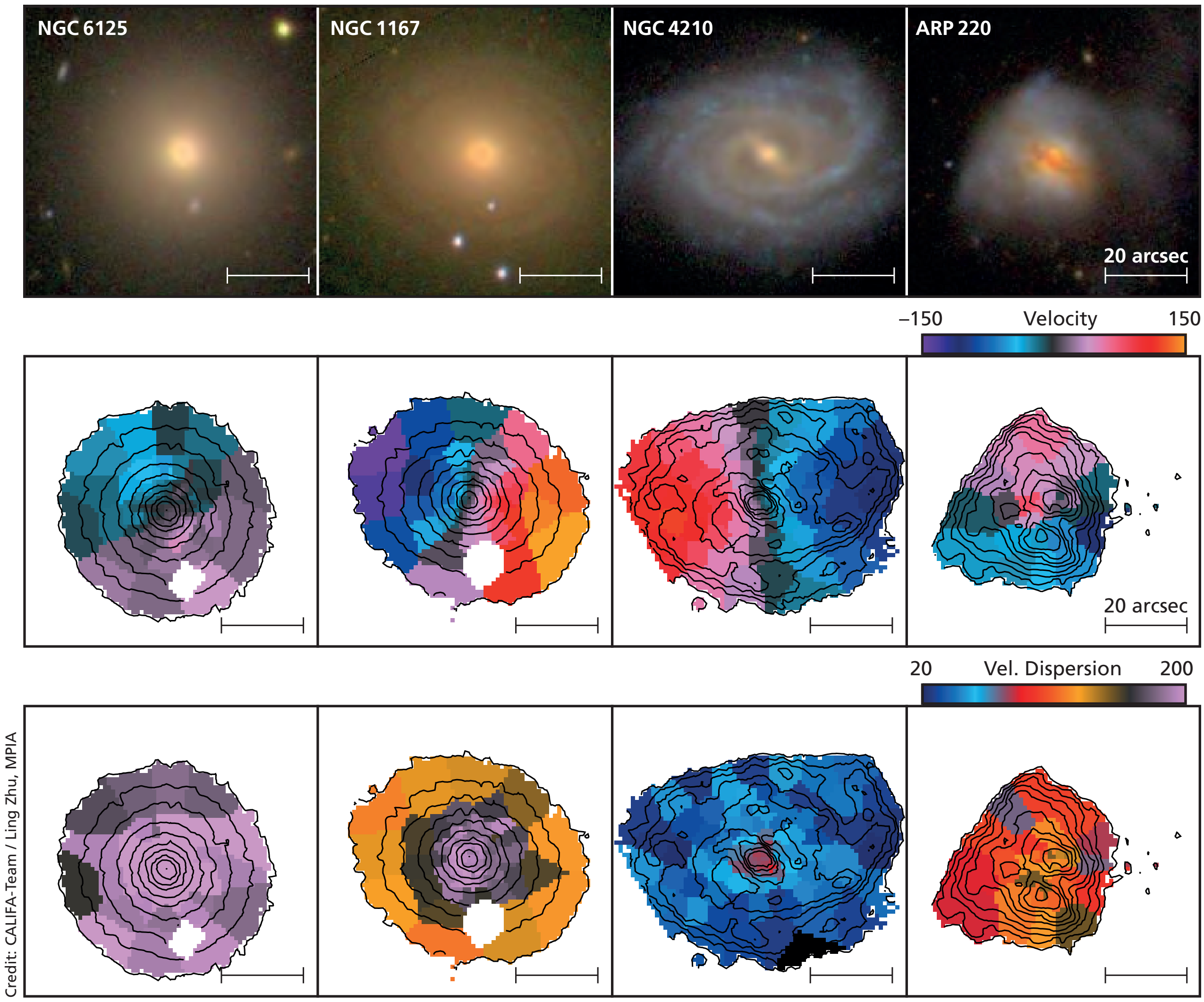


Fig. II.5.1: Four galaxies from the CALIFA survey. The top row shows SDSS images of the galaxies. The center row shows a map of the average stellar velocity within the galaxy; in blue regions stars are, on average, moving towards us, and in red regions away from us. The bottom row shows whether motion is uniform or mixed – i.e. whether stars mostly follow the average motion or whether there are marked deviations from the average.

with no clear sense of rotation. Using data from a large-scale survey, a group of researchers led by Ling Zhu from the Max Planck Institute for Astronomy (MPIA) was able to reconstruct the typical orbits of stars in galaxies. The properties of these orbits tell a story about how each galaxy came into being, and are important for testing models of galaxy formation.

The data are part of the CALIFA survey, a systematic spectroscopic study of over 600 galaxies conducted using the PMAS spectrograph at the 3.5 meter telescope at Calar Alto Observatory in Spain. As part of the survey, astronomers created velocity maps of 300 galaxies, showing how stars in different parts of the galaxy move towards or away from us.

Deciphering stellar motions in galaxies

Based on their findings, researchers differentiated between near-circular stellar orbits, which they dub "cold orbits", and highly elongated "hot orbits", which are typical of a random, disordered motion of stars. By fitting various models to their data, they were then able to show that cold orbits are prevalent among smaller galaxies, whose stars have a combined mass of about 10 billion times the mass of the Sun. In the largest galaxies with over 100 billion solar masses, hot orbits are much more common. Overall, most stars are on "warm" orbits in between the two extremes.

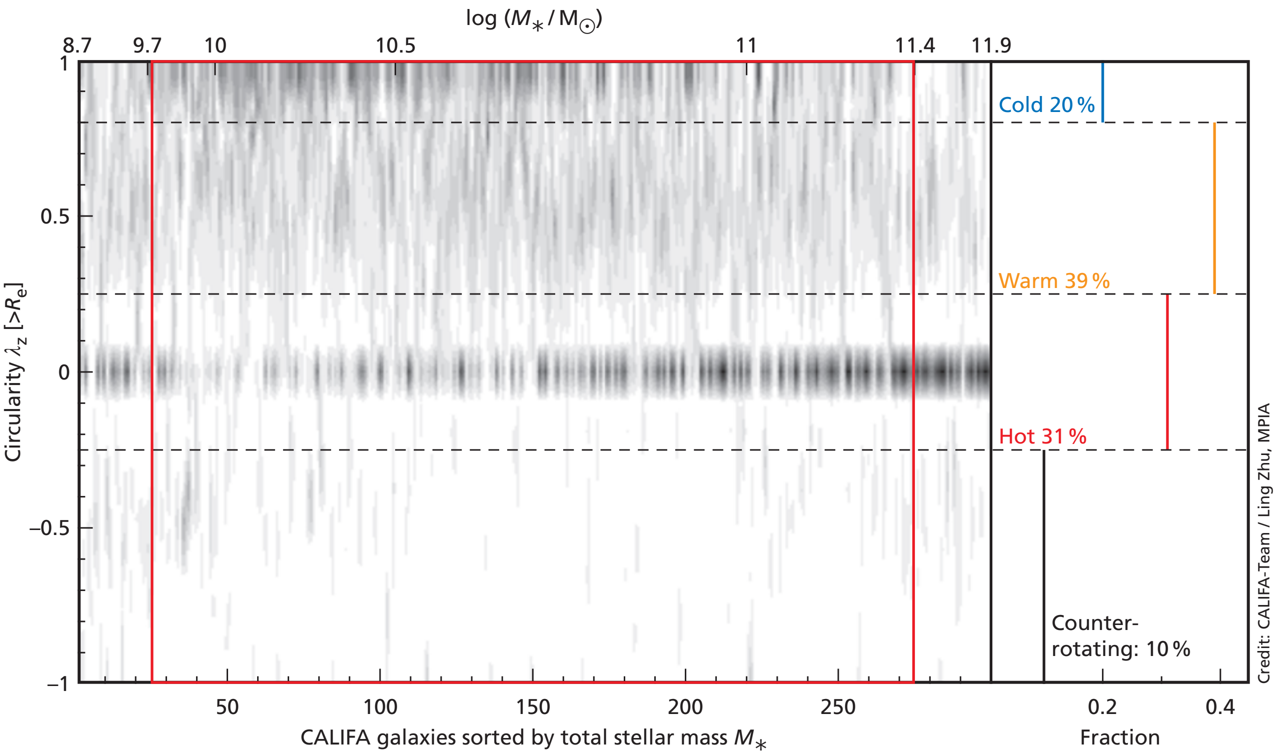
These motion maps moreover contain telltale clues about a galaxy's formation history. For instance, galaxies grow larger over billions of years by merging with other galaxies. Some galaxies, which have repeatedly accreted smaller galaxies, but never merged with another galaxy of a size similar to themselves, typically feature a thin, rotating disk of stars. Our own home galaxy, the Milky Way, is such a disk galaxy. On the other hand, if two galaxies of roughly equal mass merge the result will be an elliptical galaxy consisting of a jumble of stellar orbits oriented every which way.

Disk galaxies have a greater proportion of colder stellar orbits, given the orderly rotation of disk stars. Here, astronomers have found that the jumbled orbits within elliptical galaxies are not circular orbits at various orientations but are in fact predominantly hot orbits. In this way, the stellar orbit measurement can reliably distinguish between disk-like galaxies (colder orbits) and elliptical-like galaxies (hot orbits) – even in cases where just looking at an image of the galaxy would not allow astronomers to make that distinction.

Stellar motion tells the history of galaxies

Put differently, by measuring stellar orbits, astronomers are able to tell whether a galaxy's past has merely been a quiet succession of smaller mergers, or shaped by a

Fig. II.5.2: The orbit-circularity (λ_z) distribution for each of the 300 CALIFA galaxies, with galaxies sorted from left to right by increasing stellar mass (M_*). Each thin slice vertically represents the λ_z distribution of one galaxy. Darker color indicates higher probability density, while the right panel shows the volume-corrected average fractions of cold, warm and hot orbits.



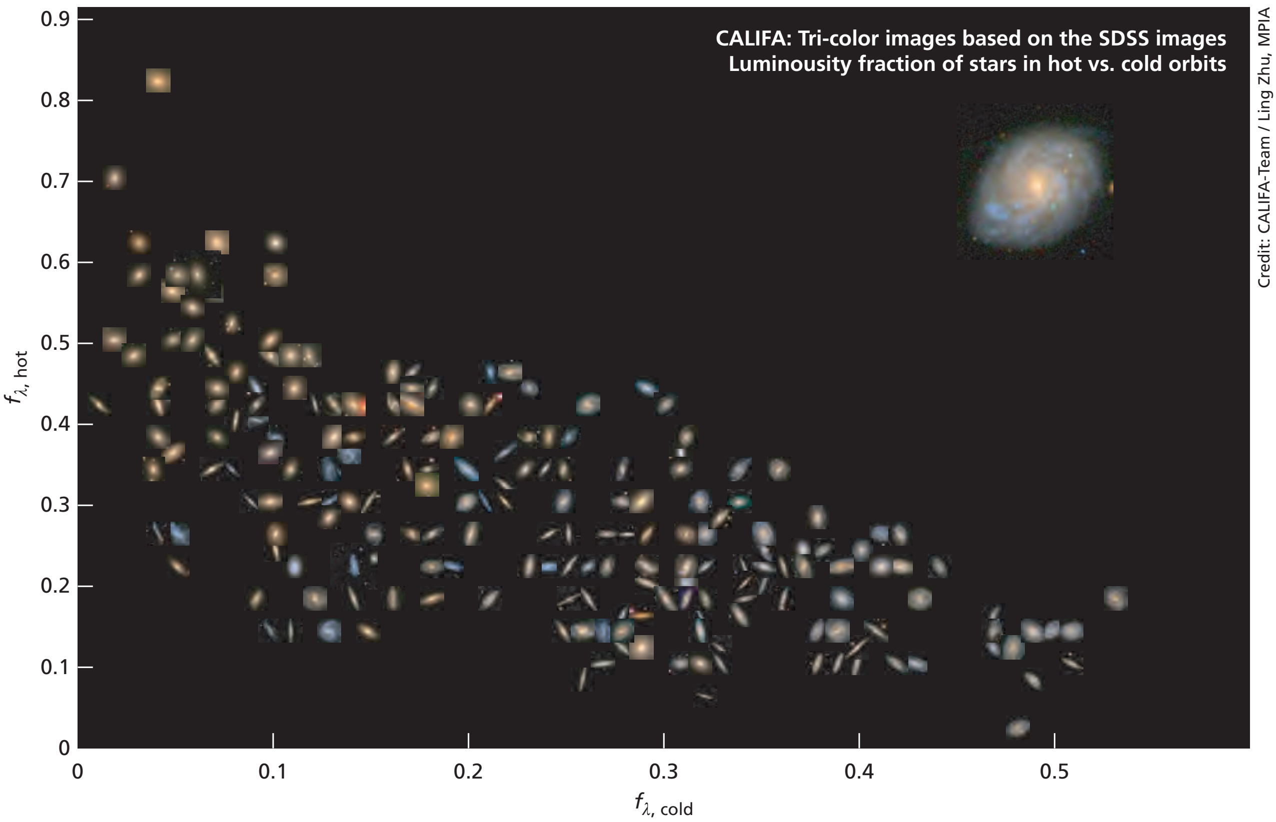


Fig. II.5.3: Diagram of stellar orbit statistics for CALIFA galaxies. The higher a galaxy's position, the larger that galaxy's fraction of hot (very elongated) orbits. The farther to the right a galaxy's position, the larger the fraction of cold (nearly circular) orbits. The fact that yellowish elliptical galaxies are mostly located top left, while bluish disk galaxies are mostly bottom right indicates the link between stellar orbit statistics and a galaxy's history.

violent major merger. This is thanks to their novel and accurate method of reading off a galaxy's history – their survey with its data sets for 300 galaxies turns out to be the largest existing library of galaxy history books!

For scientists simulating the formation and evolution of galaxies, these results are a treasure trove of new observational constraints. From the beginning, the CALIFA survey was carefully designed to yield a representative sample of galaxies. In this way, astronomers simulating galaxy evolution can now directly test whether or not their simulations provide correct predictions for the prevalence, or not, of hot, cold or warm orbits among galaxies of different masses.

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L. Zhu et al. 2018, "The stellar orbit distribution in present-day galaxies inferred from the CALIFA survey" in Nature Astronomy, Vol. 2, p. 233. DOI: 10.1038/s41550-017-0348-1

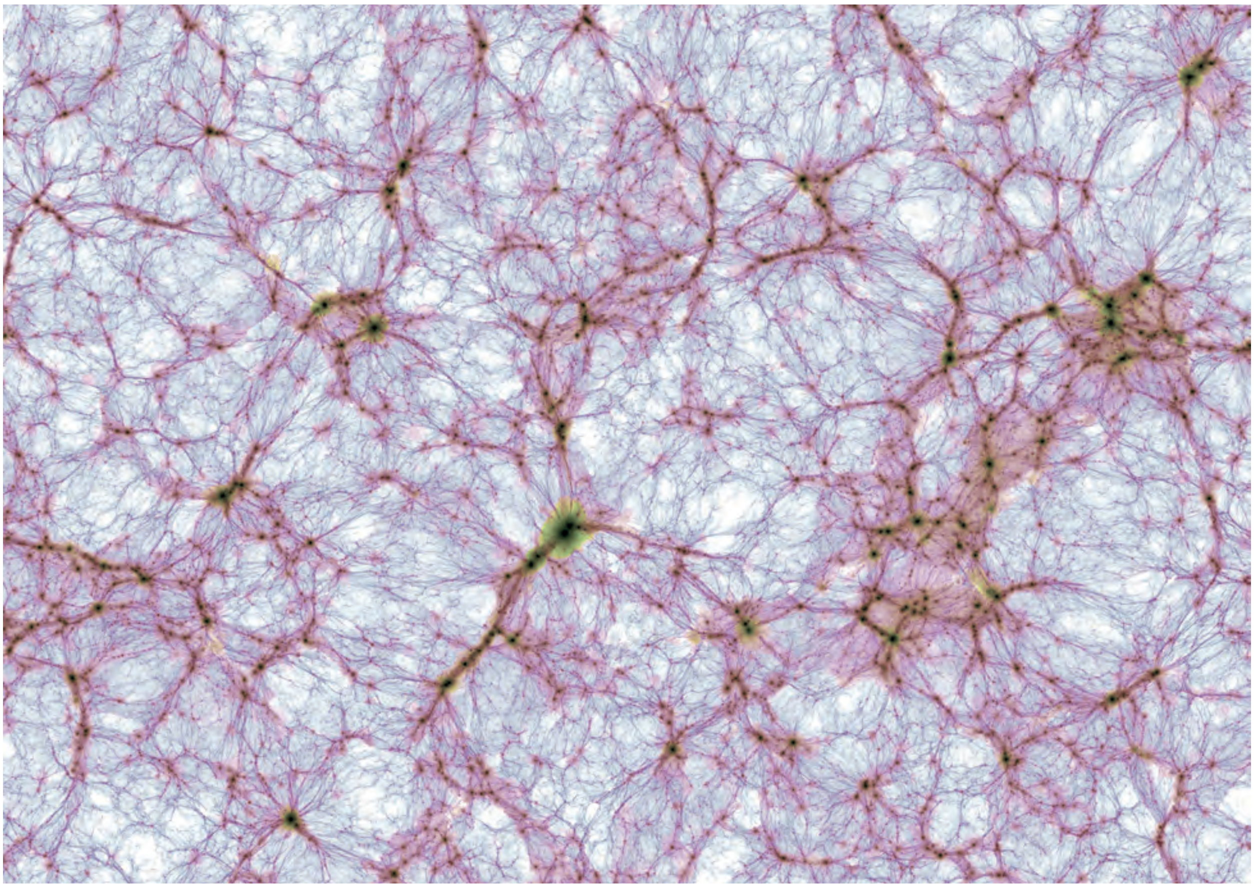
II.6 Highlights

How black holes shape the Cosmos

Astrophysicists from Heidelberg, Garching, and the United States have gained new insights into the formation and evolution of galaxies by calculating how black holes influence the distribution of dark matter, how heavy elements are produced and distributed throughout the Cosmos, and where magnetic fields originate. All of this was possible by developing and programming a new simulation model for the Universe, which created the most extensive simulations of this kind to date. The new findings are expected to help answer fundamental questions in cosmology.

Every galaxy harbors a supermassive black hole at its center. A newly developed computer model shows how these iconic mass condensations influence the large-scale structure of our Universe. The research team includes scientists from the Heidelberg Institute for Theoretical Studies (HITS), Heidelberg University, the Max-Planck-Institutes for Astronomy (MPIA, Heidelberg) and for Astrophysics (MPA, Garching), U.S. universities Harvard and the Massachusetts Institute of Technology (MIT), as well as the Center for Computational Astrophysics in New York. The project, "Illustris – The Next Generation" (IllustrisTNG) is the most complete simulation of its kind to date. Based on the basic laws of physics, the simulation shows how our Cosmos has evolved since the Big Bang. Building on the preceding Illustris project, IllustrisTNG includes some of the physical processes that play a crucial role in this evolution for the very first time in such an extensive simulation.

Fig. II.6.1: Thin slice through the cosmic large-scale structure in the largest simulation of the IllustrisTNG project. The image brightness indicates the mass density, while the color visualizes the mean gas temperature of ordinary (baryonic) matter. The displayed region extends by about 1.2 billion lightyears from left to right. The underlying simulation is presently the largest magneto-hydrodynamic simulation of galaxy formation, containing more than 30 billion resolution elements, among them being cells and particles.



Credit: IllustrisTNG Collaboration

A realistic Universe straight out of the computer

At its nodes, the cosmic web of gas and dark matter predicted by IllustrisTNG hosts galaxies quite similar in shape and size of real galaxies. For the first time, hydrodynamic simulations were able to directly compute the detailed clustering patterns of galaxies in space. When comparing the IllustrisTNG simulations with observational data – including the latest large surveys – they demonstrate a high degree of realism. In addition, the simulations predict how the cosmic web changes over time, in particular how this occurs differently in comparison to what the underlying "back bone" of dark matter would do and because of the effects of supermassive black holes and supernova explosions. "It is particularly fascinating that we can accurately predict the influence of supermassive black holes on the distribution of matter out to large scales", said principal investigator Prof. Volker Springel (HITS, MPA and Heidelberg University). "This is crucial for reliably interpreting forthcoming cosmological measurements".

Where the stars sparkle: New findings for the structures of galaxies

IllustrisTNG also improves the researchers' understanding of how the hierarchical structure of galaxies formed. Theorists argue that small galaxies should form first and then merge into ever larger objects, driven by the relentless pull of gravity. The numerous galaxy collisions literally tear some galaxies apart and scatter their stars onto wide orbits around the newly created large galaxies, which should give them a faint background glow of stellar light. These predicted pale stellar halos are very difficult to observe due to their low surface brightness. However, IllustrisTNG was able to simulate exactly what astronomers should be looking for in their data. "Our predictions can now be systematically checked by observers", pointed out Dr. Annalisa Pillepich (MPIA), who led a further IllustrisTNG study. "This yields a critical test for the theoretical model of hierarchical galaxy formation".

The most important transformation in the life cycle of galaxies

In another study, Dr. Dylan Nelson (MPA) was able to demonstrate the important impact of black holes on galaxies. Star-forming galaxies shine brightly in the blue light of their young stars until a sudden evolutionary shift ends their star formation: they thus become dominated by old, red stars, and join a graveyard full of "red and dead" galaxies. "The only physical entities capable of extinguishing star formation in our large elliptical galaxies are the supermassive black holes at their centers", explained Nelson. "The ultrafast outflows of these gravity traps reach velocities of up to 10 percent of the speed of light and affect giant stellar systems that are billions of times larger than the comparably small black hole itself".

Astrophysics with a special code and a supercomputer

For the project, the researchers developed a particularly powerful version of their highly parallel moving-mesh code AREPO and used it on the Hazel Hen machine at the High-Performance Computing Center in Stuttgart,

Fig. II.6.2: Rendering of the gas velocity in a thin slice of 100 kiloparsec thickness (in the viewing direction), centered on the second most massive galaxy cluster in the TNG100 calculation. Where the image is black, the gas is hardly moving, while white regions have velocities that exceed 1000 km/s. The image contrasts the gas motions in cosmic filaments against the fast chaotic motions triggered by the supermassive black hole sitting at the center of the deep gravitational potential well.

Credit: IllustrisTNG Collaboration

Credit: The TNG Collaboration

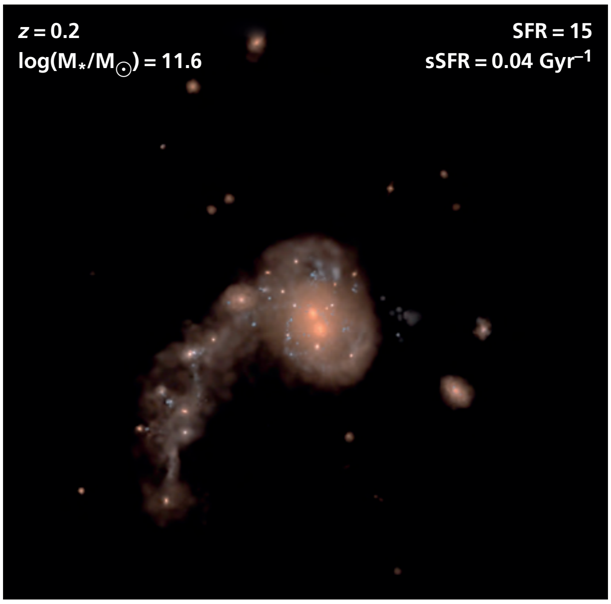


Fig. II.6.3: Still frame of a 500 kiloparsecs sized box of the IllustrisTNG simulation. A tidal arm of stars is formed during the merging of two equally sized galaxies.

Credit: The TNG Collaboration

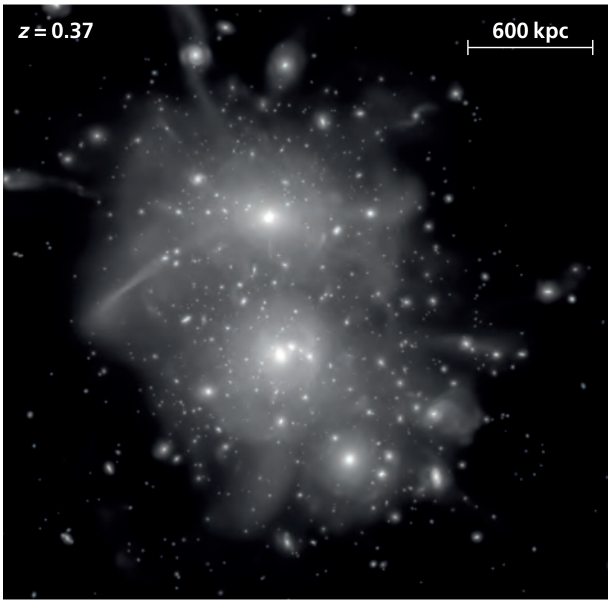


Fig. II.6.4: Snapshot from one of the IllustrisTNG calculations centered on a growing galaxy cluster with complex interactions between numerous galaxies at a redshift of $z = 0.37$. It evolves into a massive galaxy cluster similar to the Virgo cluster with a final mass of some 2×10^{14} solar masses. The actual simulation covers a cubic volume of roughly 50 Megaparsecs a side.

Germany's fastest mainframe computer, currently ranked nineteenth in the top 500. IllustrisTNG is the largest hydrodynamic simulation project that studies the emergence of cosmic structures to date. To compute one of the two main simulation runs, over 24,000 processors were used over the course of more than two months in order to follow the formation of millions of galaxies in a representative region of the Universe with nearly one billion lightyears on a side. "Thanks to the computing time obtained from the German Gauss Centre for Supercomputing, we have been able to redefine the state of the art in this field", clarified Volker Springel. "The new simulations produced more than 500 terabytes of simulation data. Analyzing this huge mountain of data will keep us busy for years to come, and it promises many exciting new insights into different astrophysical processes".

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D. Nelson, A. Pillepich, V. Springel et al. 2018, "First results from the IllustrisTNG simulations: the galaxy colour bimodality" in Monthly Notices of the Royal Astronomical Society, Vol. 475, Issue 1, p. 624. DOI: 10.1093/mnras/stx3040

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II.7 Highlights

Migration of stars

A group of astronomers led by Maria Bergemann from the Max Planck Institute for Astronomy have investigated a small population of stars in the halo of the Milky Way Galaxy, finding its chemical composition to closely match that of the Galactic disk. This similarity provides compelling evidence that these stars originated from within the disk, rather than from merged dwarf galaxies. The reason for this stellar migration is thought to be theoretically proposed oscillations of the Milky Way disk as a whole, induced by the tidal interaction of the Milky Way with a passing massive satellite galaxy.

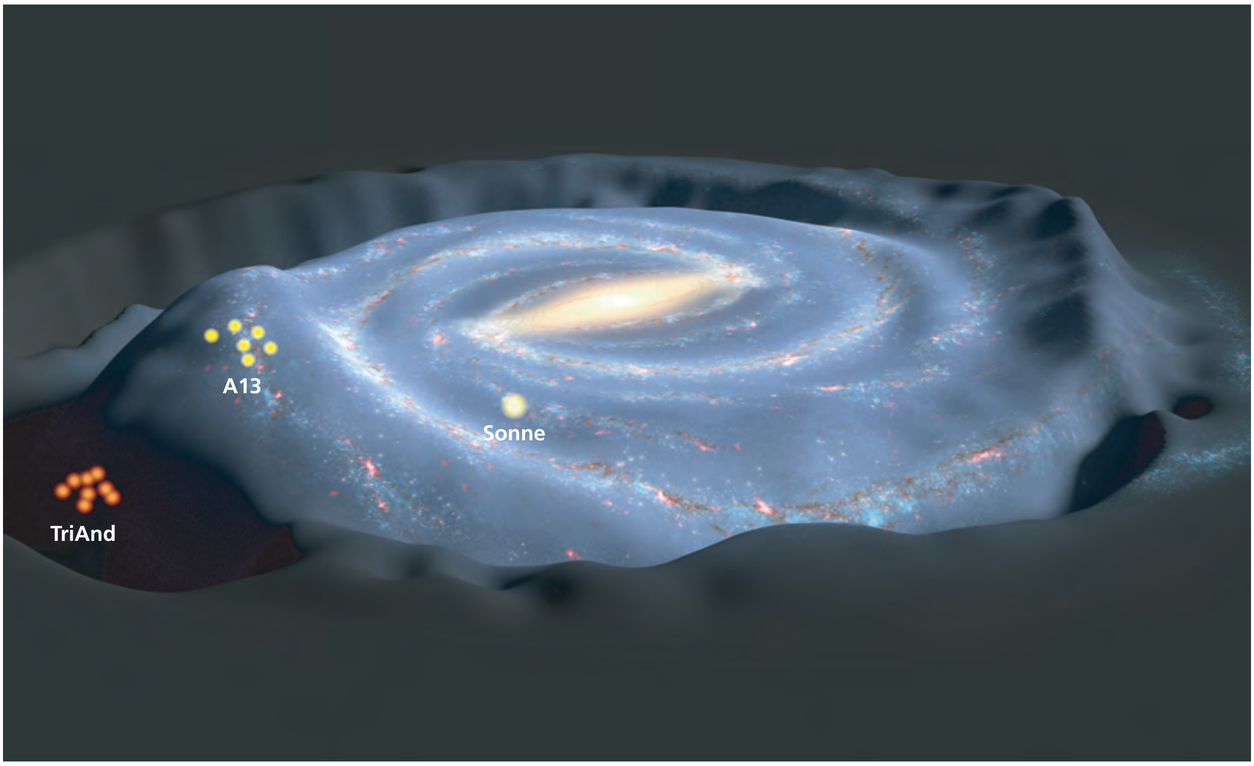
If anyone from outer space would like to contact you via "space mail", your cosmic address would include several more lines including "Earth", "Solar System", "Orion Spiral Arm" and "Milky Way Galaxy". This position within our home galaxy gives us a front row seat to explore what is happening in such a galaxy.

However, our internal perspective presents some challenges in our quest to understand it – for instance in outlining its shape and extent. And yet another problem is time: How can we interpret galactic evolution if our own life span (and that of our telescopes) is far less than the blink of the cosmic eye?

Today we have a fairly clear picture of the broad properties of the Milky Way and how it fits among other galaxies in the Universe. Astronomers classify it as a rather average, large spiral galaxy with the majority of its stars circling its center within a disk, and a dusting of stars orbiting in the Galactic halo.

Stellar streams and stellar clouds in the halo

These halo stars do not seem to be randomly distributed around the halo, but instead many are grouped together in giant structures – immense streams and overdensities



Credit: NASA/JPL-Caltech / C. Laporte / Thomas Müller, MPIA

Fig. II.7.1: The Milky Way galaxy perturbed by the tidal interaction with a dwarf galaxy, as predicted by N-body simulations. The locations of the observed stars above and below the disc, which are used to test the perturbation scenario, are indicated.

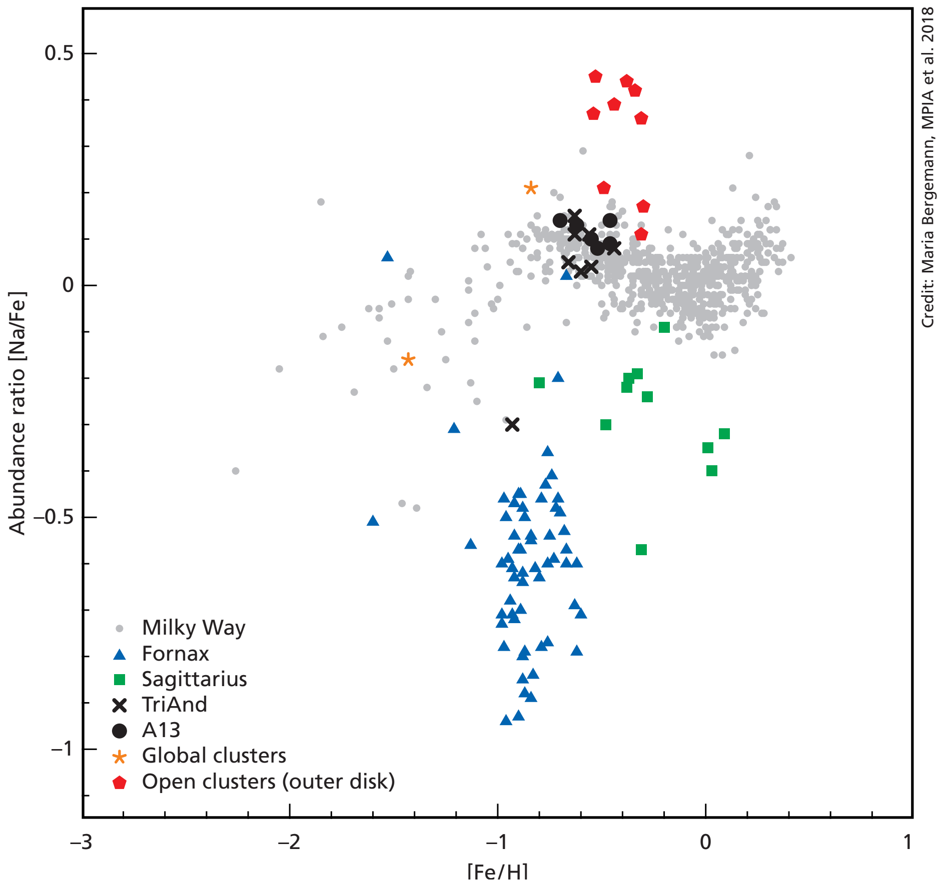


Fig. II.7.2: Chemical abundance ratios of elements (hydrogen, iron, sodium) in stars that belong to different populations of the Milky Way, as measured from stellar spectra. The two stellar groups TriAnd and A13 are chemically very similar to the stars in the Milky Way disk. [A/B] stands for the logarithm of the ratio of A to B, relative to the value of the Sun.

of stars, some entirely encircling the Milky Way. These structures have been interpreted as signatures of the Milky Way's tumultuous past – debris from the gravitational disruption of the many smaller galaxies that are thought to have invaded our Galaxy in the past.

Researchers are attempting to learn more about this violent history of the Milky Way by looking at the properties of the stars in the leftover debris. Their positions and motions can provide us clues of the original path of the invader, while the types of stars they contain and the chemical compositions of those stars can tell us something about what the long-dead, disrupted galaxy might have looked like.

Not intruders, after all?

An international team of astronomers lead by Dr. Maria Bergemann from the Max Planck Institute for Astronomy has found compelling evidence that some of these halo structures might not be leftover debris from invading galaxies but rather originate from the Milky Way's disk itself.

The team of scientists investigated 14 stars located in two different structures in the Galactic halo, the Triangulum-Andromeda (Tri-And) and the A13 stellar overdensities, which lie at opposite sides of the Galactic disk plane. Earlier studies of the motions of stars in these two diffuse structures revealed that they are moving in a similar way and might be related to the Monoceros Ring, a ring-like structure that twists around the Galaxy. However, the nature and origin of the two stellar structures was still not conclusively clarified. Their position could be determined as each lying about 5 kiloparsecs (14,000 lightyears) above and below the Galactic plane as indicated in Figure II.7.1.

For the first time, Bergemann and her team have presented detailed chemical abundance patterns of these stars, obtained with high-resolution spectra taken with the 10 meter Keck telescope and 8.2 meter VLT (Very Large Telescope, ESO). "The analysis of chemical abundances is a very powerful test that allows, in a way similar to DNA matching, us to identify the parent population of the star. Different parent populations, such as the Milky Way disk or halo, dwarf satellite galaxies or globular clusters, are known to have radically different chemical compositions. So once we know what the stars are made of, we can immediately link them to their parent populations", explained Bergemann.

Tracing the origin of stars with chemistry

When comparing the chemical compositions of the stars in the A13 and TriAnd structures with the ones found in other parts of the Milky Way galaxy, the scientists were surprised to find that the chemical compositions were almost identical, both within and between these groups, and closely matched the abundance patterns of the Milky Way disk stars. This provides compelling evidence that these stars most likely originate from the Galactic thin disk (the younger part of Milky Way, concentrated towards the Galactic plane) itself, rather being debris from invasive galaxies.

But how did the stars get to these extreme positions above and below the Galactic disk? Theoretical calculations of the evolution of the Milky Way galaxy predict this scenario, with stars being relocated to large vertical distances from their place of birth in the disk plane. This migration of stars is theoretically explained by the global oscillations of the Milky Way disk. The favored explanation for these oscillations (or waves) is the tidal interaction of the Milky Way's Dark Matter halo and its disk with a passing massive satellite galaxy.

A dynamic home galaxy

These findings are very exciting, as they indicate that the Milky Way galaxy's disk and its dynamics are significantly more complex than previously thought. "We showed that it may be fairly common for groups of stars in the disk to be relocated to more distant realms within the Milky Way – having been kicked out by an intruding satellite galaxy. Similar chemical patterns may also be found in other galaxies, indicating a potential galactic universality of this dynamic process", said Allyson Sheffield from LaGuardia Community College/CUNY, co-author on the study.

As a next step, the astronomers plan to analyze the spectra of other stars both in the two overdensities as well as stars in other stellar structures further away from the disk. They are also very keen on obtaining the masses and ages of these stars in order to constrain the time limits when this interaction of the Milky Way and a dwarf galaxy happened.

"We anticipate that ongoing and future surveys such as Gaia, GALAH and 4MOST will provide unique information about the chemical composition and kinematics of stars in these overdensities. The two structures we have analyzed already are, in our interpretation, associated with large-scale oscillations in the disk, induced by an interaction of the Milky Way and a dwarf galaxy", said Bergemann.

Indeed, more recent studies published in September 2018 and in January 2019 (Antoja et al., 2018, Nature 561, 360; Bland-Hawthorn et al., 2019, MNRAS, stz217 respectively) support this conclusion. Both investigations use high-quality kinematic and positional data taken with the Gaia satellite and confirm the picture of a Milky Way disk undergoing large-scale oscillations, which are likely to have been caused by an encounter with a massive dwarf galaxy.

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M. Bergemann et al. 2018, "Two chemically similar stellar overdensities on opposite sides of the plane of the Galactic disk" in Nature, Vol. 555, p. 334. DOI: 10.1038/nature25490

II.8 Highlights

Gaia provides most complete census of stars and dust

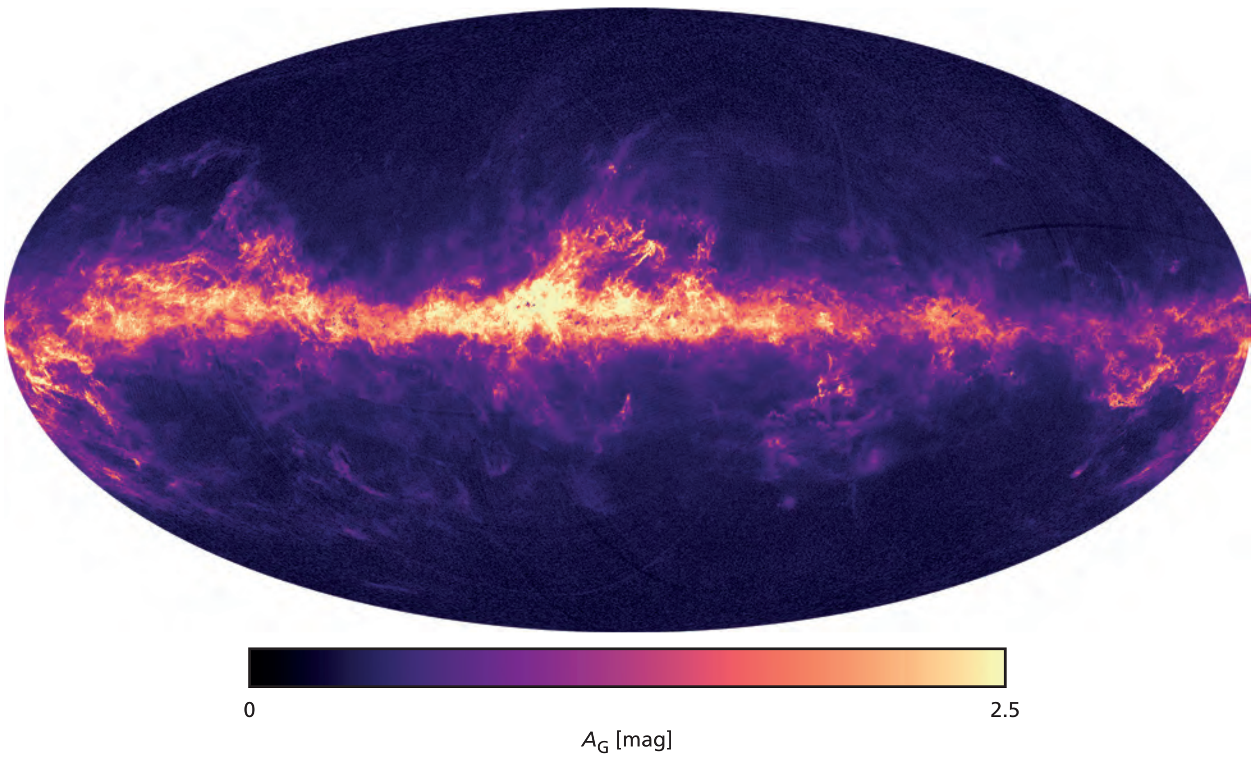
The new data release of ESA's Gaia satellite not only includes data that allows astronomers to compute accurate distances for 1.33 billion stars. Researchers based at the Max Planck Institute for Astronomy have also used Gaia's measurements to derive the physical properties of almost 80 million stars, making this the largest stellar census yet. At the same time, the analysis provides the most detailed three-dimensional map of dust in our home galaxy yet, which promises to put the analysis of celestial objects on a more solid footing than before.

ESA's Gaia satellite is first and foremost an astrometry satellite: using a simple geometric concept (namely the parallax method) and highly accurate stellar position measurements, the satellite has collected data that allows astronomers to determine the distances and stellar motions for 1.33 billion stars, and thus to map our cosmic neighborhood with breathtaking precision. Determining such distances is essential for understanding the physical properties of astronomical objects – after all, an object with a given observed brightness could be rather dim but comparatively near, or emit lots of light but be very far away. Without distance measurements, we cannot tell which. Almost all astronomical distance measurements depend on the kind of geometric measurement employed by Gaia. With its high-precision data, Gaia securely "anchors" distance measurements throughout astronomy.

Accurate physical properties for millions of stars

But in addition to measuring stellar positions with high precision, Gaia also provides precise brightness measurements for three different wavelength bands (corresponding to three different colors called G broad-band, BP and RP band) for 1.38 billion sources. These measurements provide valuable clues as to the astrophysical properties of the objects in question. This is where the data analysis group CU8 comes in, which is managed by Coryn Bailer-Jones of the Max Planck Institute for Astronomy and part of Gaia's Data Processing and Analysis Consortium (DPAC).

Fig. II.8.1: Extinction map based on the Gaia DR2 data.



Credit: René Andrae et al. 2018

Credit: ESA / Gaia / DPAC; Morgan Fouesneau / René Andrae / Coryn Bailer-Jones / O. Creevey

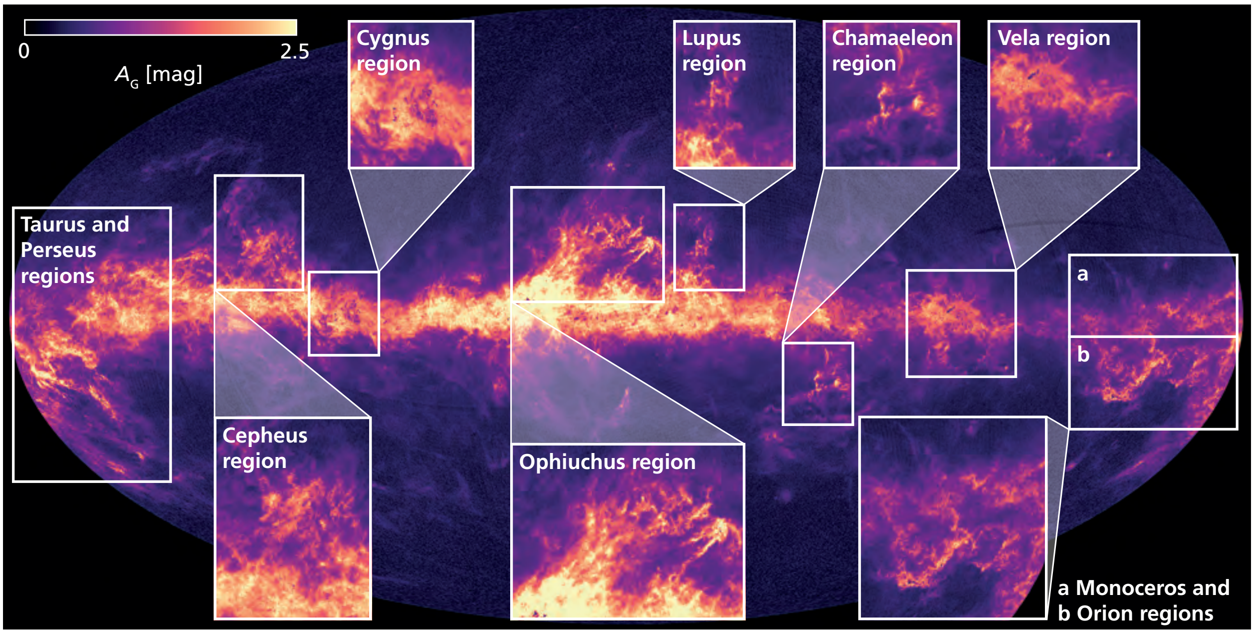


Fig. II.8.2: Annotated version of the Gaia DR2 extinction map. The underlying map uses an equal-area all-sky projection (also known as Mollweide projection) oriented along the Galactic coordinates. The Galactic center is in the middle of the map, while the Northern Galactic Pole is at the top. The color scale indicates the mean extinction value derived for the spatial cells probed in the analysis.

Bailer-Jones and his colleagues are experts in deriving astrophysical quantities from the Gaia data. From the brightness measurements, they were able to estimate the effective temperatures for 161 million stars among those observed by Gaia, and derive the luminosities (that is, the amount of energy emitted per unit of time) and the radii for 77 million of those stars. This is the largest uniformly derived set of physical properties to date. The results were included as part of the new Gaia data release DR2.

Starlight altered by dust

The astronomers working on this study also extracted information about the dust content of our cosmic neighborhood from their analysis. The space between stars is not empty but rather filled with dust and gas clouds. When starlight travels through a dust cloud, some of the light is scattered, and thus when we observe such a star, it appears a little dimmer and redder than without the dust, an effect known as extinction. For light at different wavelengths – different colors – the effect varies: light at shorter wavelengths (towards the blue end of the spectrum) is scattered more strongly than at longer wavelengths (the red end of the spectrum). This characteristic wavelength-dependence allows astronomers to reconstruct the extent of the extinction starlight has undergone.

The extinction towards 88 million stars along with the stars' physical properties has been determined in this project. A map of these extinction values can be seen in Fig. II.8.1 Combined with these stars' three-dimensional positions, which are derived from Gaia's astrometric measurements, the extinction values towards these stars are sufficient data to construct a three-dimensional map of dust distributed within the range probed by Gaia.

On the far left side of Fig. II.8.2 are the Taurus and Perseus cloud complexes. On the right is the Orion molecular cloud complex, a small part of which can be seen with the naked eye as the Orion nebula. This cloud, the California nebula in the constellation Perseus, and the Ophiuchus cloud complex just above the Galactic center show exquisite substructures.

A 3d extinction map of the visible Milky Way

The extinction derived from the Gaia data will allow astronomers to reconstruct the three-dimensional dust density of the Milky Way (Fig. II.8.3), thereby gaining key insight into the distribution of the interstellar medium – the gas and dust between the stars. The interstellar medium is the material out of which stars are born. Stars, in turn, heat up the interstellar medium and, when they die, seed it with the chemical elements they have produced via nuclear fusion over the course of their lives.

The dust in the interstellar medium absorbs light at short wavelengths (UV), scattering and re-emitting it at long wavelengths (IR). Dust shields molecules from destruction. This is crucial for the formation of

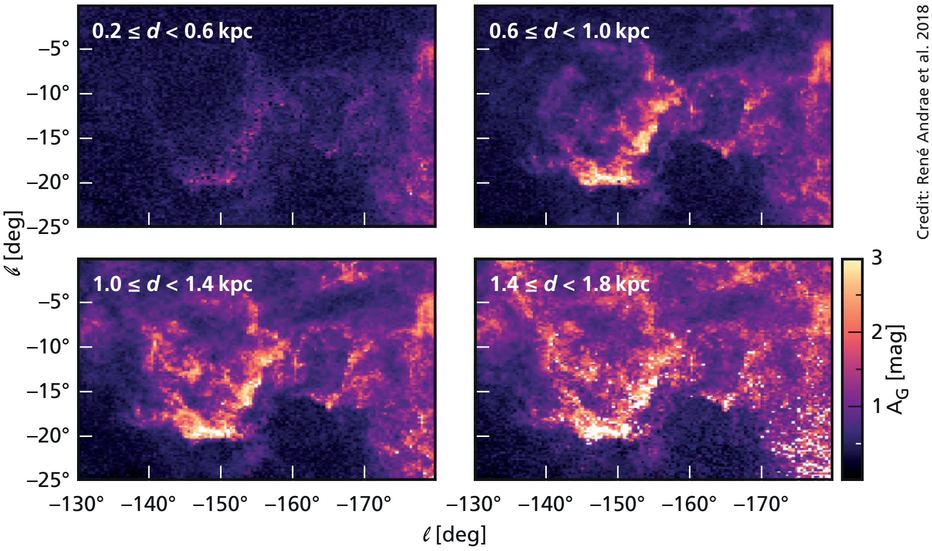


Fig. II.8.3: Extinction estimates toward Orion for different distance slices, from sources with parallax precisions better than 20 %. White points lack extinction estimates.

planets and for the kind of molecules that end up as part of newly forming planets. Studying the properties of dust, such as its three-dimensional distribution and variations in density, is crucial to understanding the physics of this balance. It provides us with important clues to the physical mechanisms of the formation of stars and of galaxies, and to the history of our home galaxy. In Heidelberg, these clues will find fertile ground – the city hosts a collaborative research center funded by Deutsche Forschungsgemeinschaft, SFB881 "The Milky Way System", dedicated to research on our home galaxy.

All in all, the new Gaia data is a treasure trove of information about our home galaxy, and will influence astronomy for years to come.

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R. Andrae et al. 2018, "Gaia Data Release 2: First stellar parameters from Apsis" in Astronomy & Astrophysics, Vol. 616, A8. DOI: 10.1051/0004-6361/201732516

C. A. L. Bailer-Jones et al. 2018, "Estimating Distance from Parallaxes. IV. Distances to 1.33 Billion Stars in Gaia Data Release 2" in The Astronomical Journal, Vol. 156, Issue 2, p. 58. DOI: 10.3847/1538-3881/aacb21

II.9 Highlights

Astronomers witness the birth of a planet

Scientists from the Max Planck Institute for Astronomy (MPIA) in Heidelberg and the SPHERE instrument consortium at the Very Large Telescope of the European Southern Observatory (ESO) in Chile have discovered and characterized an extremely young exoplanet in a state of its formation. This gas giant with the designation PDS70b, which has a mass equivalent to several Jupiters, was detected orbiting the star PDS70 within a gap of its protoplanetary disk. This means that PDS70b is still in the vicinity of its birth place and likely still accumulating material. The observations provide a unique opportunity to test models of planet formation and to probe the early history of planetary systems, including our own Solar System.

So far, the search for exoplanets has revealed about 4000 specimens of various sizes, masses and distances from their parent stars. However, we do not know exactly how these planets form. While there are various theories and models for planet formation, until now actually observing the birth of a planet has proven very difficult.

But this is exactly what astronomers of the Max Planck Institute for Astronomy (MPIA) in Heidelberg and the consortium of the SPHERE instrument at the Very Large Telescope of the European Southern Observatory (ESO) have achieved: The planet PDS 70 b was discovered at a distance of 22 astronomical units (AU) from its host star PDS 70. 1 AU is the mean distance between the Sun and the Earth. "For our study, we selected PDS 70, a star that was already suspected of having a young planet circling around it", says Miriam Keppler, a doctoral student at the MPIA and first author of the publication that highlights the discovery.

Disk around a young star

PDS 70, a 5.4 million year old so-called T Tauri star, is surrounded by a circumstellar disk of gas and dust whose radius is 130 AU. For comparison: the outer edge of the Solar System, the Kuiper Belt, only extends to about 50 AU. Such disks consist of matter left over from the host star's formation. The circumstellar disk around PDS 70 exhibits a large gap. These gaps are thought to be signs of ongoing planet formation, caused by a young giant planet collecting disk material on its orbit. By interacting with the disk, the planet slowly changes its orbit around the central star. Over time, it then cuts a broad circular swathe through the gas and dust.

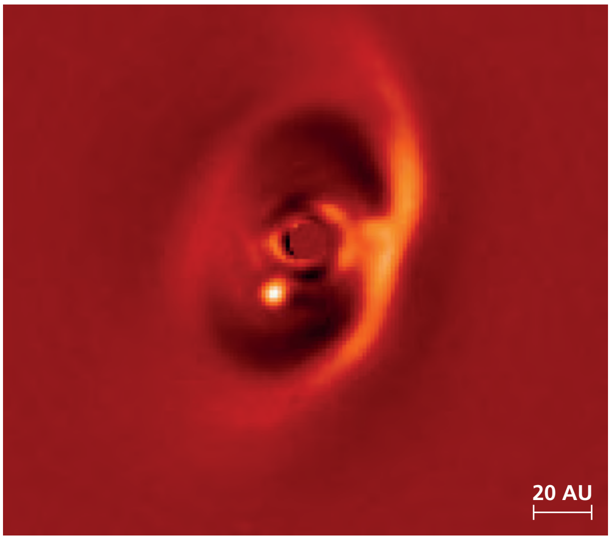
In a subsequent investigation led by André Müller, the group of astronomers was able to obtain a spectacular image of the PDS 70 system, in which the planet is clearly visible at the inner rim of the disk's gap. The planet takes about 120 years to orbit its host star. A spectrum of PDS 70 b allowed the astronomers to determine the planet's atmospheric and physical properties. "This discovery provides us with an unprecedented opportunity to test theoretical models of planet formation", Müller explained with enthusiasm.

A young, giant planet

The analysis shows PDS 70 b to be a giant gas planet, with a mass a few times that of Jupiter. This mass is enough to heavily impact the structure of the gas in the circumstellar disk, as follow-up observations with the Atacama Large Millimeter/submillimeter Array (ALMA) show (Keppler et al, 2019, Astronomy & Astrophysics, 625, A118).

The planet's surface has a temperature of around 1200 Kelvin, making it much hotter than any planet in our own Solar System. The planet must be younger than its host star and is probably still growing – a scenario which

Fig. II.9.1: Near infrared image of the PDS 70 disk obtained with the SPHERE instrument. The young exoplanet PDS 70 b is clearly detected as a bright signal at the inner rim of the gap (*dark region*). The emission coming from the central star was masked out. The bar to the lower right indicates the linear scale of the image at a distance of 370 light years.



Credit: ESO / André Müller, MPIA

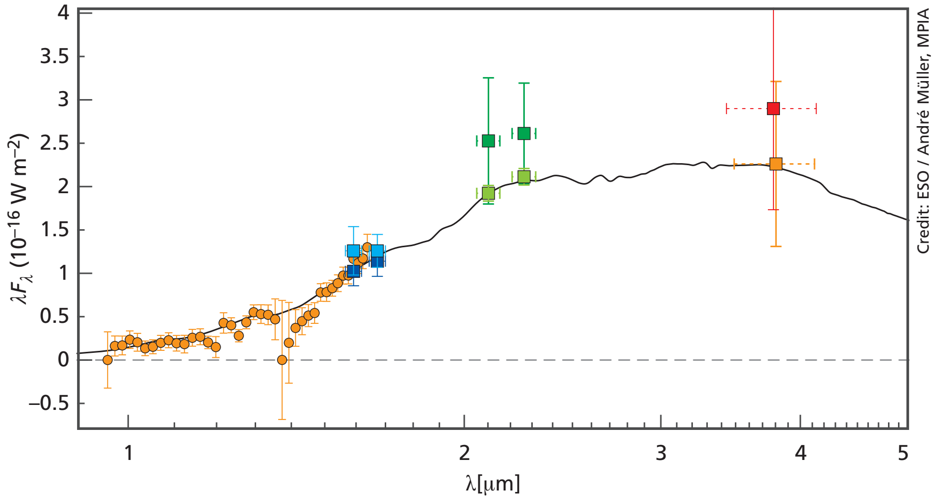


Fig. II.9.2: Spectrum of the young planet PDS 70 b, obtained by combining ESO SPHERE and NACO observations and supplemented by data retrieved from the Gemini/NICI archive (*dots and squares with error bars*). The black line shows an atmospheric model that describes the measurements best. It was used to derive the planet's temperature and mass. The axes denote the wavelength (horizontal) and the measured intensity (vertical).

is supported by the recent detection of H_α emission at the location of PDS 70 b by a team led by Kevin Wagner. The H_α line is a common tracer for accretion, i. e., for the transport of material onto the planet (K. Wagner et al., 2018, Astrophysical Journal Letters, 863, L8).

The data also indicate that the planet is surrounded by clouds that alter the radiation emitted by the planetary core and its atmosphere. "We corrected our calculations to take into account the new distance estimate determined by the Gaia satellite. According to Gaia, PDS70 is at a distance of 370 light years", Keppler explains. PDS70 b confirms the prediction that gas planets like Jupiter should indeed form at large distances from the host star.

To obtain an image of a protoplanetary disk, scientists need to apply sophisticated observational and analytical techniques. On conventional images, all objects in the vicinity of the host star are lost in the glare of the bright starlight. However, with the SPHERE instrument the contribution of the star can be strongly reduced. To do this, the camera makes use of a property of light known as polarisation. Linearly polarised light waves oscillate in only one plane, while the light of a star is predominantly non-polarised. In contrast, light reflected by the disk will become linearly polarised when scattered by the disk's dust particles.

With a suitable polarisation filter, which transmits light waves in only one plane of oscillation, the light coming from different areas of the disk is either detected or cancelled out, depending on the filter's orientation. Incidentally, photographers use a similar effect to suppress reflections from a smooth surface.

The starlight, on the other hand, will be observed regardless of the orientation of the filter. By exploiting this difference between direct starlight and light reflected by the disk, astronomers can remove the direct starlight. In support of their measurements, observers also cover the star with a mask. What remains is an image of the disk.

"After ten years of developing new powerful astronomical instruments such as SPHERE, this discovery shows us that we are finally able to find and study planets at the time of their formation. That is the fulfilment of a long-cherished dream", concludes Prof. Thomas Henning, director at MPIA, senior author of the two studies and the German co-I of the SPHERE instrument.

Miriam Keppler, André Müller, Thomas Henning, Roy van Boekel, Faustine Cantalloube, Anne-Lise Maire (now University of Liège), Adriana Pohl (now Carl Zeiss SMT GmbH), Matthias Samland, Henning Avenhaus

in collaboration with

Myriam Benisty, Gaël Chauvin (Univ. Grenoble Alpes, CNRS and Unidad Mixta Internacional Franco-Chilena de Astronomía), Anthony Boccaletti (LESIA, Observatoire de Paris), Silvano Desidera (INAF – Osservatorio Astronomico di Padova), Christian Ginski, Rob van Holstein (Leiden Observatory)

M. Keppler, M. Benisty, A. Müller, Th. Henning et al. 2018, "Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70" in Astronomy & Astrophysics, Vol. 617, A44. DOI: 10.1051/0004-6361/201832957

A. Müller, M. Keppler, Th. Henning et al. 2018, "Orbital and atmospheric characterization of the planet within the gap of the PDS 70 transition disk" in Astronomy & Astrophysics, Vol. 617, L2. DOI: 10.1051/0004-6361/201833584

II.10 Highlights

The boiling atmosphere of the hottest known exoplanet

Astronomers have found that the atmosphere of the hottest known exoplanet, the hot Jupiter-like planet KELT-9b, is "boiling off", with the escaping gas being captured by the host star. Using the CARMENES instrument at Calar Alto Observatory, Fei Yan and Thomas Henning of the Max Planck Institute for Astronomy in Heidelberg were able to detect the escaping hydrogen atmosphere of the planet. Their observations indicate a spread-out hydrogen envelope that is being pulled towards the host star.

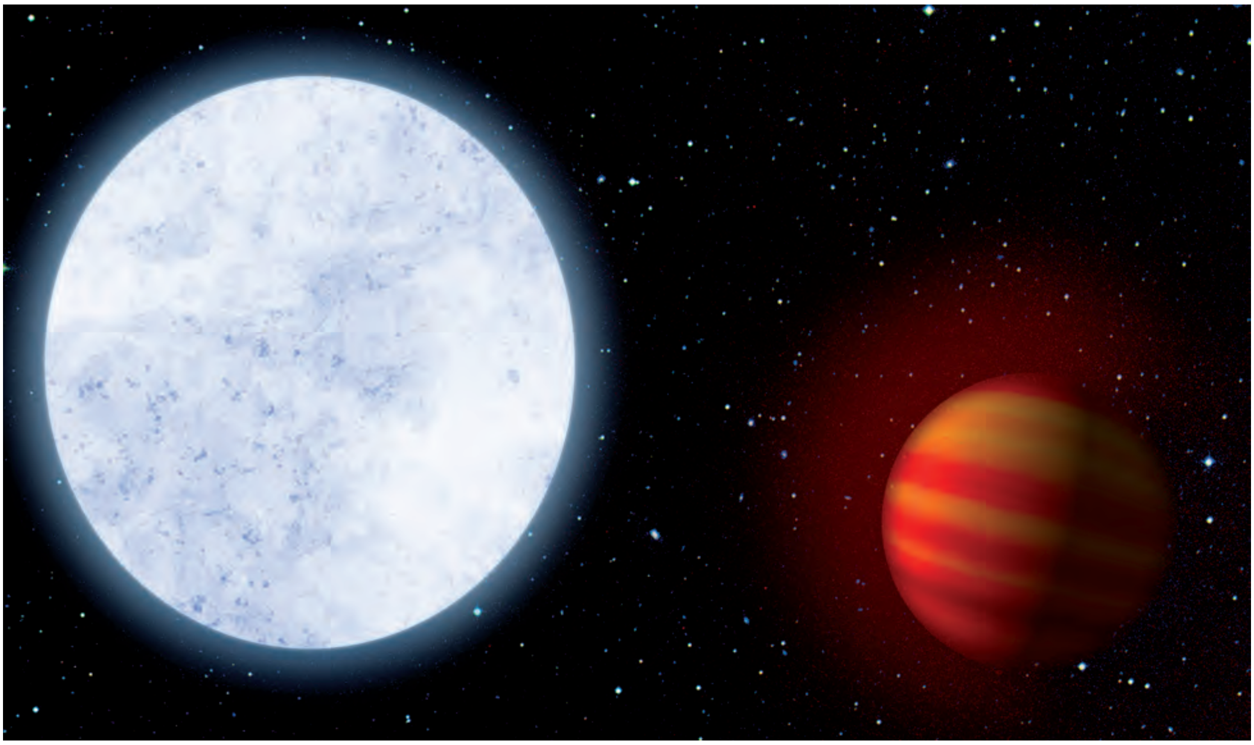
By all definitions, KELT-9b is a hellish kind of exoplanet: Due to its proximity to an extremely hot host star, the planet itself is the hottest exoplanet discovered to date. Fei Yan and Thomas Henning of the Max Planck Institute for Astronomy (MPIA) have detected this planet's extended atmosphere, showing that the star is not only heating up the planet's hydrogen atmosphere – it is then using its gravity to pull the hydrogen onto itself.

A hot star with a hot planet

Specifically, the planet's host star KELT-9 is an extremely hot star with a temperature of up to 10,000 K (compared to the Sun's much more modest 5800 K, or 5500 degrees Celsius). The planet's orbit is extremely small – ten times smaller than the orbit of Mercury in our Solar System (corresponding to only about 3 % of the diameter of Earth's orbit around the Sun). When the planet was discovered in 2017 by a team of astronomers led by B. Scott Gaudi (Ohio State University), the astronomers measured its day-side temperature to be at 4600 K (4300 degrees Celsius), which is hotter than many stars.

The planet itself is a significantly larger version of our Solar System's Jupiter, at almost 3 times Jupiter's mass and almost twice Jupiter's diameter. Combined, these properties place KELT-9b firmly in the class of what astronomers call "hot Jupiter".

Fig. II.10.1: Artist's impression of the hot star KELT-9 and its planet KELT-9b, a hot Jupiter. Researchers have detected the extended hydrogen atmosphere of the planet, which is "boiling off" due to the central star's great heat.



Credit: MPIA

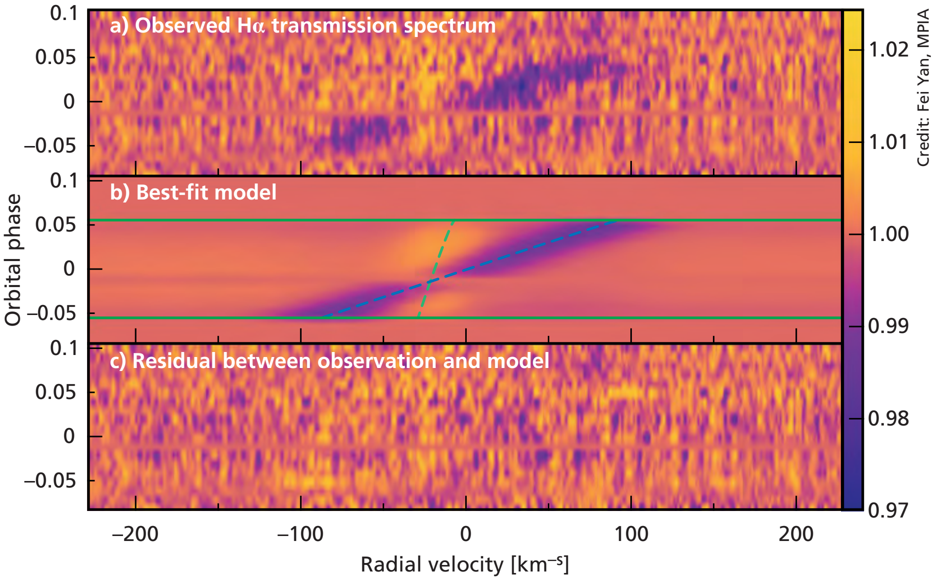


Fig. II.10.2: The change of the Hα absorption line while KELT-9b obscures its host star. The panels indicate how well the observations agree with a model that provides the best match to the data. (*a*) Observed Hα transmission spectrum. (*b*) Best-fit model. The model includes a Hα transmission spectrum modified by the Doppler shift caused by the planet's motion. (*c*) The residual after subtracting the model from the data. The vertical axis represents the orbital phase during the planetary transit. The horizontal axis indicates the radial velocity calculated from the measured wavelength of the Hα line relative to its line center. The colors depict the ratios between the observed spectra and a reference spectrum that was obtained from the spectra taken outside the transit.

The planet's orbit regularly takes it between the host star and an observer on Earth. During each such transit, the planet blocks some of the starlight, causing the star to dim a little bit as measured by telescopes on Earth. The planet was initially discovered by astronomers looking for this kind of regular little dip in the star's apparent brightness (the so-called transit method).

The planet loses its atmosphere to the star

When Yan and Henning observed KELT-9b using the CARMENES spectrograph installed at the 3.5 meter telescope at Calar Alto Observatory, they found traces of the planet's atmosphere. Whenever the planet was in front of its star, there would be a clear absorption line for hydrogen (H_α), a narrow wavelength region where the planet's hydrogen-rich atmosphere absorbs some of its host star's bright light. CARMENES gives a particularly detailed, high-resolution view of stellar spectra making it an excellent tool for this kind of observation.

The extended hydrogen atmosphere surrounding KELT-9b is surprisingly large – more than half as large again as the planet's radius. Models of how the star's gravity pulls on the planet's gas show that this is close to the maximal size of such an atmosphere. The large extent suggests that the planet is losing hydrogen gas at a significant rate of more than 100,000 tons per second. The star is "boiling off" the planet's atmosphere and, in a blatant case of interplanetary theft, is pulling the gas onto itself.

The way the wavelength of the absorption line changes during the transit amounts to a rare direct detection of the planet's motion: the wavelength shift is due to the Doppler shift, which tells us how fast the planet is moving towards us or away from us. Fei Yan, lead author of the article, said, "This is a very special kind of measurement – this kind of direct measurement of planetary motion has only been possible for about half a dozen exoplanets so far".

Thomas Henning, director at the MPIA and co-author of the study, said, "This planet reminds me of the mythical Icarus, who came too close to the Sun and crashed. Our planet will not crash, but it will certainly lose an essential part of itself, namely its atmosphere".

Fei Yan (now University of Göttingen),
Thomas Henning

in collaboration with

the CARMENES consortium

F. Yan and Th. Henning 2018, "An extended hydrogen envelope of the extremely hot giant exoplanet KELT-9b" in Nature Astronomy, Vol. 2, Issue 9, p. 714. DOI: 10.1038/s41550-018-0503-3

II.11 Highlights

Testing the predictions of general relativity near the Milky Way's central black hole

For the first time, astronomers have clearly detected the effects predicted by general relativity for the orbit of a star around the Milky Way's central supermassive black hole. The measurements took advantage of the closest approach of one particular star to the black hole in May 2018. The required high precision was provided by the GRAVITY instrument at ESO's Very Large Telescope, which exploits the wave properties of light to allow for highly accurate relative positions of point sources.

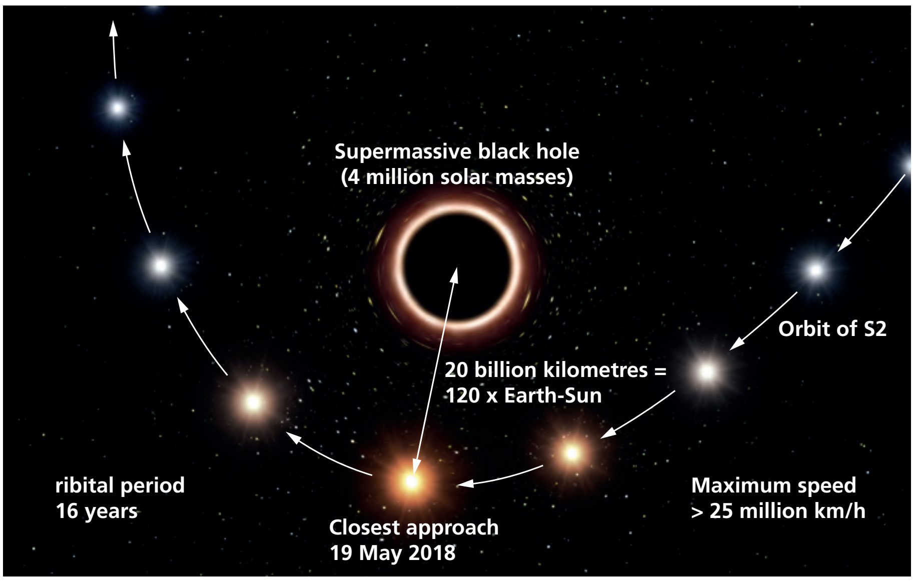
The central black hole of our home galaxy, the Milky Way, is one of the best studied black holes in the cosmos. Detailed information about the black hole's mass and compactness has come from studies of stars orbiting the black hole in the galactic center. A team of astronomers led by Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics [MPE]) including astronomers Wolfgang Brandner and Thomas Henning from the Max Planck Institute for Astronomy (MPIA) has published the most detailed motion study of its kind so far.

Using the GRAVITY instrument, co-developed at MPIA for the European Southern Observatory's Very Large Telescopes, the astronomers were able to monitor the orbit of the star named S2 during its closest possible fly-by near the black hole. The result clearly shows the effects of Einstein's general relativity on the star's orbit and is the first definite detection of such relativistic properties of a stellar orbit around a black hole.

A compact object in the center of our Galaxy

According to current knowledge, supermassive black holes in the centers of galaxies are the rule, not the exception. When astronomical telescopes became sufficiently powerful in the mid-1990s, a research group led by Reinhard Genzel and a few years later another team led by Andrea Ghez at UCLA independently began to track the motion of stars near the galactic center. Their data clearly showed that these stars were orbiting an object with a mass of about 4 million times that of the Sun. Although the object is almost invisible using ordinary light, radio astronomers had detected it earlier as the radio source "Sagittarius A*" (pronounced Sagittarius A star).

Data obtained of stars that pass fairly close to that central mass have ruled out all other known astronomical objects (such as very compact star clusters), which could account for the mass. To the best of our knowledge, the central object is indeed, as described by Einstein's theory of general relativity, a black hole. This is defined as a region with a mass so compactly concentrated that not even light can escape that region's gravitational pull; matter and light can fall in, but what has fallen in is trapped



Credit: ESO / Martin Kornmesser

Fig. II.11.1: This artist's impression shows the path of the star S2 as it passes very close to the supermassive black hole at the center of the Milky Way. As it gets close to the black hole the very strong gravitational field causes the color of the star to shift slightly to the red, an effect of Einstein's general theory of relativity.

there forever. The radio waves we detect are thought to be emitted by a plasma disk of matter orbiting the black hole before spiraling in.

This defining property of black holes makes it impossible to test predictions of general relativity for their interiors. However, this study does the next best thing, namely testing the predictions for gravitational effects in the direct vicinity of the black hole, and in particular the deviations of general relativity's predictions from the behavior expected of systems governed by classical, Newtonian gravity.

Astronomical geometry with light waves

For detecting the effects of general relativity, the timing had to be just right. The orbit of the star S2 is highly eccentric, i. e. not a circle but an elongated ellipse. At the star's closest approach to the black hole, known as the orbit's pericenter or peribothron (the latter derived from the Greek bothros for hole or pit), the speed of S2 is highest, reaching values of about 7650 kilometers per second, which corresponds to 2.6 % of the speed of light.

Every 16 years (the orbital period of S2), this close passage provides particularly favorable conditions for observing relativistic effects, which are most pronounced at high speeds and at an object's closest approach to a mass. The most recent close approach was on May 19, 2018, affording a rare opportunity to astronomers. Genzel said, "This is the second time that we have observed the close passage of S2 around the black hole in the center of the Milky Way. But this time, because of much improved instrumentation, we were able to observe the star with unprecedented resolution". Compared to the previous observations of a closer approach in 2002, the accuracy has increased by a factor of more than 10.

Even under these fortunate conditions, the relativistic effects are comparatively small, and thus require considerable observational sophistication. As a key instrument, the astronomers used GRAVITY, which was designed with exactly this particular application in mind. GRAVITY can combine near-infrared light from all four 8.2 meter telescopes of the European Southern Observatory's Very Large Telescope (VLT) in Chile in a way that makes use of the wave properties of light, using a technique known as interferometry. One particular advantage of this method is that it allows astronomers to determine the relative position of two point sources of light with extreme precision.

Using GRAVITY, the astronomers were able to track the closest approach of S2 to the black hole with a precision of better than 30 micro-arcseconds – equivalent to tracking the relative position of two candles on the Moon with an accuracy less than 6 centimeters. Wolfgang Brandner (MPIA), co-investigator of the GRAVITY project, said, "GRAVITY is so sensitive that we can detect infrared radiation from matter in close orbit around the black hole with less than five minutes of exposure times – that is what allows for these highly precise position measurements". MPIA was responsible for GRAVITY's adaptive optics (AO) systems. They mitigate the blurring effect of Earth's atmosphere on the light from distant objects, a necessary prerequisite for the interferometric measurements.

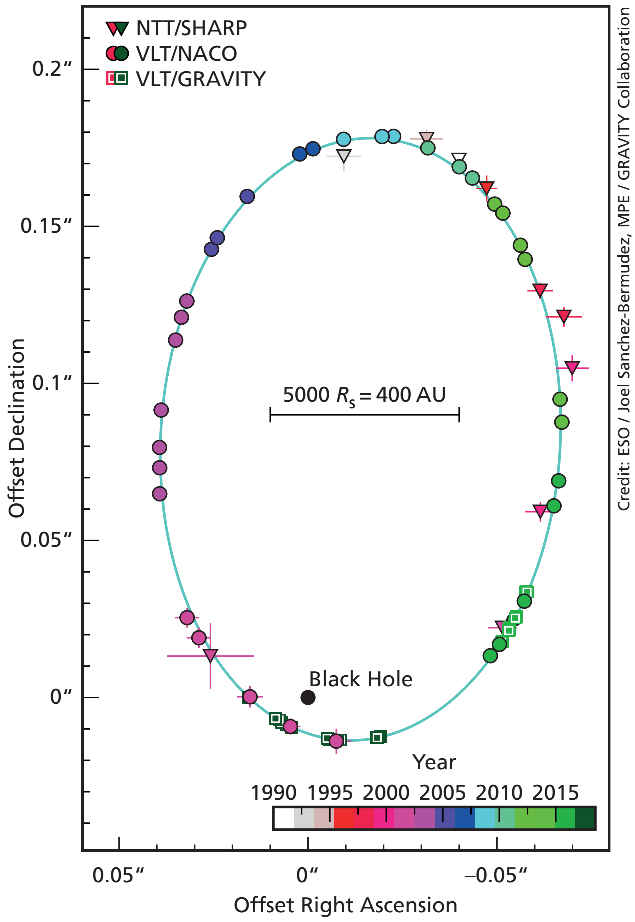


Fig. II.11.2: This diagram shows the motion of the star S2 around the supermassive black hole at the center of the Milky Way. It was compiled from observations using ESO telescopes and instruments over a period of more than 25 years.

For the analysis, the GRAVITY data were combined with data from two additional VLT instruments: the SINFONI spectrograph, which traces how S2 moves directly towards or away from us, as well as larger-scale images from the NACO instrument, which was also co-developed and built at MPIA and has traced stellar orbits around the galactic center since 2001.

General relativity passes another test

The results were unambiguous: Newtonian gravity cannot explain the observed orbit of S2 near the pericenter. Instead, the observations clearly show the combined effects of both the fast motion of S2 and the black hole's

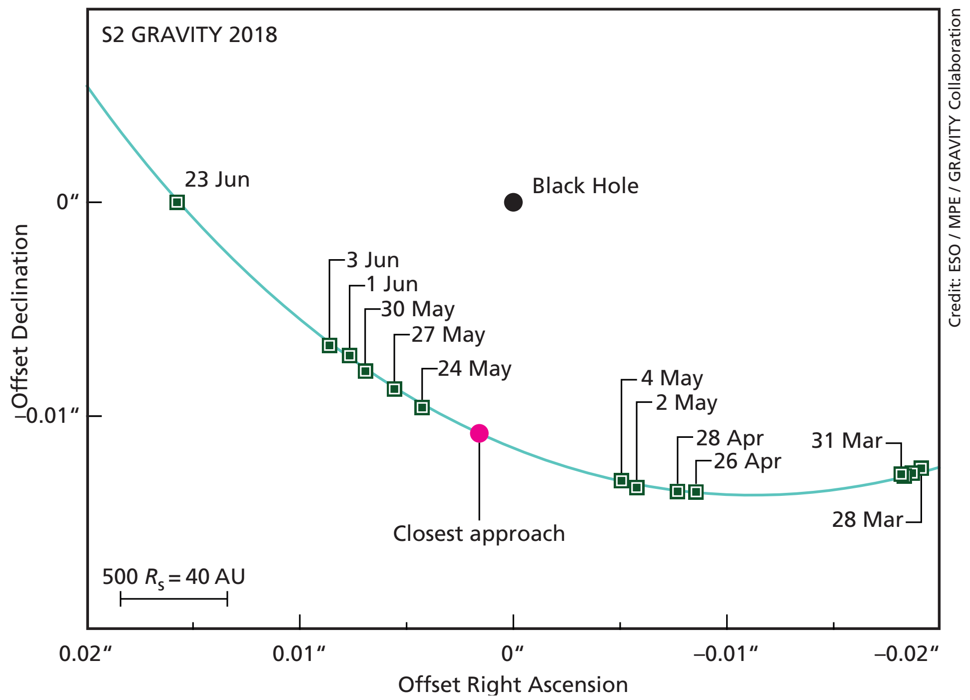


Fig. II.11.3: This diagram shows the motion of the star S2 as it passes close to the supermassive black hole at the center of the Milky Way. It demonstrates how accurately S2 was traced during its closest approach to the galactic center.

gravitational field on the orbital dynamics (specifically, time dilation for moving objects as predicted by special relativity and the gravitational redshift predicted by general relativity's equivalence principle).

Assuming there are no significant masses between S2 and the central black hole, the observations confirm the general relativistic prediction for the orbit to within ± 15 % – well within the observational uncertainty. Based on these sensitive observations, the astronomers were able to exclude light emitting material as another potential source of gravity. However, an undetected stellar black hole remains a theoretical possibility.

When reporting the results, Thomas Henning, director at the MPIA and co-author of the article, said, "This is an excellent example of the impact of observational astronomy. Before GRAVITY, observations at this level of precision would have been impossible. With this impressive result, the GRAVITY instrument is exceeding our wildest expectations".

Observations of our galaxy's central black hole with GRAVITY and other instruments are continuing. By 2020, the researchers hope to be able to detect an additional effect predicted by general relativity: the Schwarzschild precession, a slow rotation of the entire elliptical orbit around the black hole. For the star S2, that rotation amounts to about 0.2 degrees per orbit. They also hope to find out more about the matter circling, and about to fall into, the black hole – the matter whose faint glow permitted comparing Sgr A*'s position with S2's orbital path in the first place.

Wolfgang Brandner, Thomas Henning,
Stefan Hippler, Sarah Kendrew (now ESA),
Martin Kulas, Rainer Lenzen,
Eric Müller (ESO),
Joel Sanchez-Bermudez (now UNAM),
José Ramos, Ralf-Rainer Rohloff, Silvia Scheithauer
as part of the GRAVITY Collaboration

in collaboration with

Reinhard Genzel
(Max Planck Institute for Extraterrestrial Physics)
in conjunction with collaborators around the world,
at the Paris Observatory–PSL,
the Université Grenoble Alpes, CNRS,
the University of Cologne,
the Portuguese CENTRA –
Centro de Astrofisica e Gravitação and ESO

GRAVITY Collaboration et al. 2018, "Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole" in Astronomy and Astrophysics, Vol. 615, L15. DOI: 10.1051/0004-6361/201833718

II.12 Highlights

Tracking the interstellar object 'Oumuamua to its home

A team of astronomers led by Coryn Bailer-Jones of the Max Planck Institute for Astronomy (MPIA) has tracked the interstellar object 'Oumuamua to several possible home stars. The object was discovered in late 2017 – the first time astronomers have been able to observe an astronomical object from another star system visiting the Solar System. Bailer-Jones and his colleagues used data from ESA's astrometry satellite Gaia to find four plausible stars where 'Oumuamua could have begun its long journey, more than a million years ago.

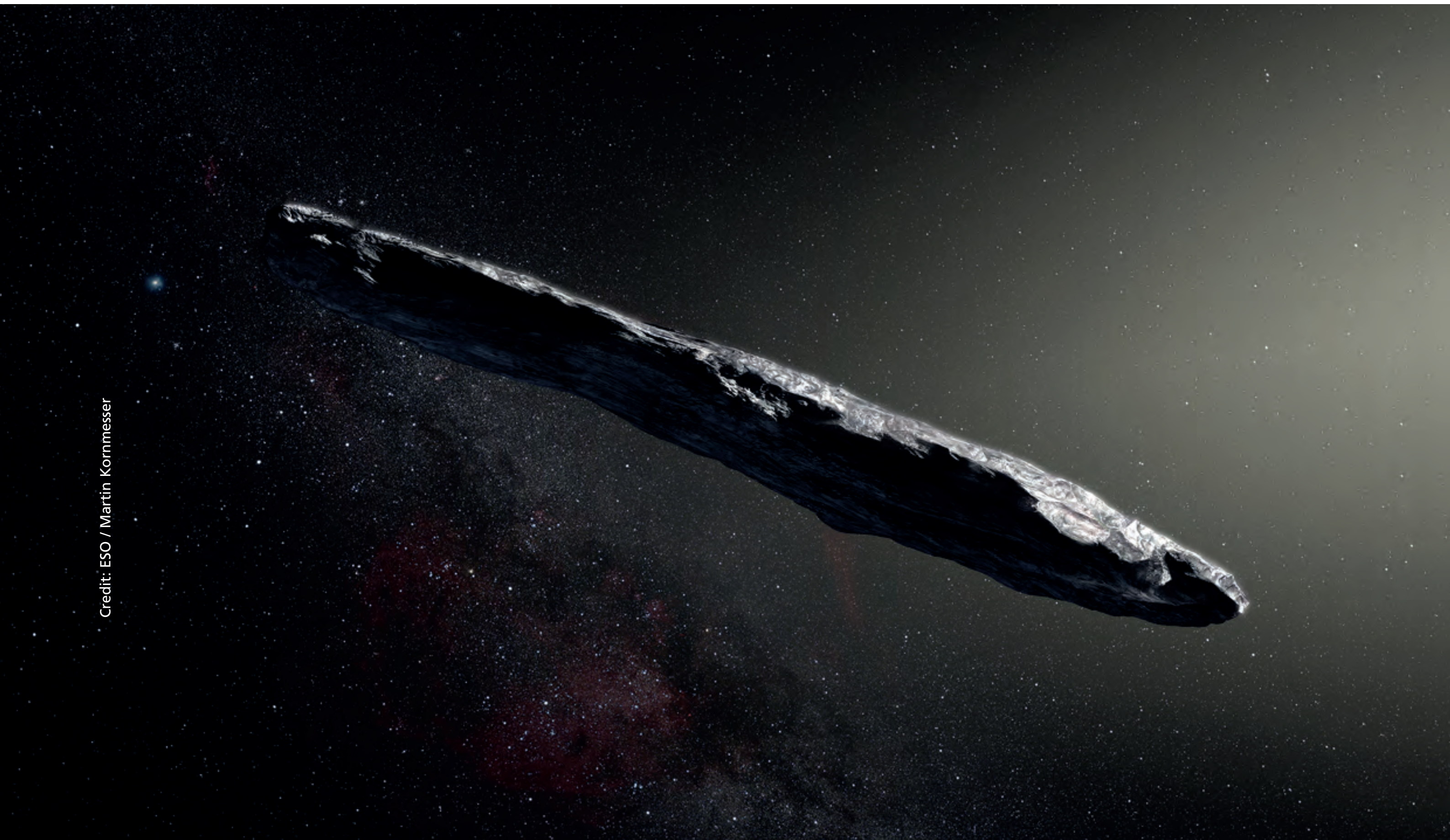
The discovery of the interstellar object now known as 'Oumuamua in October 2017 was a premiere: for the first time, astronomers were able to trace an interstellar object visiting our Solar System. Unfortunately, the visitor was only caught just as it was leaving, however astronomers were still able to use ground-based and space telescopes to measure the object's motion.

As a result, a group of astronomers led by Coryn Bailer-Jones has managed to back-track 'Oumuamua's motion and identify four candidate stars where the interstellar object could have originated. Earlier studies had attempted similar reconstructions of 'Oumuamua's origin, but had not come up with plausible candidates.

A crucial new ingredient

These earlier studies were missing a crucial ingredient: in June 2018, a group led by ESA astronomer Marco Micheli had shown that 'Oumuamua's orbit within the Solar System is not that of an object in free fall, that is, of an object moving exclusively under the influence of gravity. Instead, it was subject to some additional acceleration when the object was close to the Sun. One possible explanation is outgassing – similar to comets that release gas when they are sufficiently heated by sunlight. Like a propellant, the gas accelerates comets like an exceedingly weak rocket engine. If the anomalous acceleration is caused by outgassing, then other observations suggest it is of a different kind than what we have observed so far with comets. An alternative idea is that if 'Oumuamua were of very low density or had an extremely porous structure – and that is not something we can determine from the data – then it may have a low enough mass to area ratio for solar radiation pressure to cause the anomalous acceleration.

Fig. II.12.1: Artist's impression of the interstellar object 'Oumuamua. The object is either elongated as in this image, or shaped like a pancake.



The new study by Bailer-Jones and his colleagues takes into account how ‘Oumuamua's trajectory had changed as the object passed close to the Sun, which provides a precise estimate of the direction the object originally came from (Fig. II.12.3), as well as the speed at which it entered the Solar System.

Leveraging Gaia's treasure trove of data

This might help attempts to clarify how ‘Oumuamua entered the Solar System. But what about the stars it encountered on its way, and their combined gravity that influenced the object's trajectory? For this part of the reconstruction, Bailer-Jones made use of a treasure trove of data that ESA's Gaia mission released in April 2018, Gaia's Data Release 2 (DR2). As the leader of one of the groups in charge of preparing Gaia data for use by the scientific community, Bailer-Jones is very much familiar with this particular data set. In particular, DR2 includes precise information about positions, on-sky motion, and parallax (as a measure of distance), for 1.3 billion stars. For seven million of those, there is also information about the stars' radial velocity, that is, their motion directly away from or towards us. Using the astronomical data base Simbad, the study included 220,000 additional stars for which radial velocities are not available in Gaia DR2.

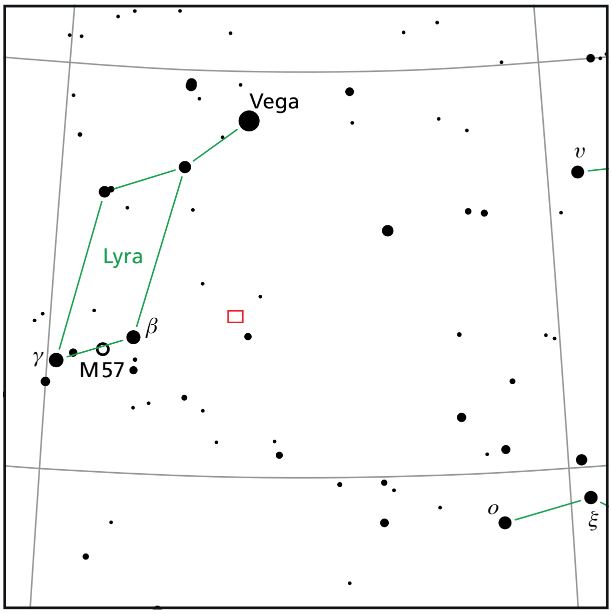
Next, the astronomers working on the data performed an approximate backtracking using a simplified scenario in which ‘Oumuamua and the stars move along straight lines and at constant speeds. From this, they selected about 4500 stars that were promising candidates for a closer encounter with ‘Oumuamua. In a next step, they traced the past motions for ‘Oumuamua and the candidate stars using a smoothed-out version of the gravitational influence of all the matter in our home galaxy (the “smoothed-out galactic potential”).

Looking for candidate homes

Various studies had already suggested that ‘Oumuamua was ejected from its home star's planetary system while forming its planets. In this early phase, there are many small-sized objects (“planetesimals”) flying around that interact with giant planets in the system. The object's home star is likely to have two key properties: tracing back ‘Oumuamua's orbit should have led the scientists performing the analysis directly back to, or at least very close to, the home star. In addition, the relative speed of ‘Oumuamua to its home star is likely to be comparatively slow. Objects are not typically ejected from their home systems at large speeds.

Bailer-Jones and his colleagues found four stars that are possible candidates for ‘Oumuamua's home world, all four of which are dwarf stars. The star that came closest to ‘Oumuamua, at least about one million years ago, is the reddish dwarf star HIP 3757. They approached each other within about 0.6 pc (1.96 lightyears). Given the uncertainties unaccounted for in this reconstruction, this result is close enough for ‘Oumuamua to have originated from its planetary system (if the star has one). However, the comparatively large relative speed (roughly 25 km/s) makes it less probable that this is ‘Oumuamua's home.

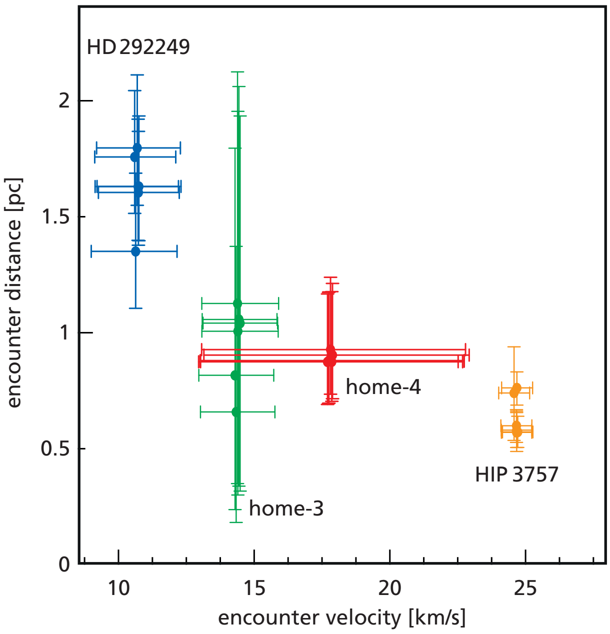
Fig. II.12.2: Artist's impression of ‘Oumuamua showing the alternative interpretation of it being shaped like a pancake.



Credit: MPIA

Fig. II.12.3: Reconstructed area from where 'Oumuamua entered the Solar System (*red rectangle*). Due to the long travel, the stars we see there were not necessarily there when 'Oumuamua passed through.

Fig. II.12.4: Encounter distance vs. velocity between 'Oumuamua and the four main home candidate stars (colors) for six solutions each, obtained from the Gaia data. The circles show the median of the encounter distributions, while the error bars span the 90 % confidence interval.



Credit: Coryn Bailer-Jones, MPIA et al. 2018

The next candidate, HD 292249, is similar to our Sun. During its encounter with 'Oumuamua about 3.8 million years ago, it was a little bit farther away from the object's trajectory (1.6 pc = 5.23 lightyears), but with a smaller relative speed of 10 km/s. The two additional candidates met 'Oumuamua 1.1 and 6.3 million years ago, respectively, at intermediate speeds and distances (see Fig. II.12.4). These other two stars have been previously catalogued by other surveys, although little is known about them.

Further directions

While these four stars are plausible candidates, the smoking gun is still missing. In order to have ejected 'Oumuamua at the observed speeds, the home system would have needed to feature a suitable giant planet that could have catapulted 'Oumuamua into the depths of space. So far, no such planet has been detected around these stars – but since none of the stars have been examined closely for planets so far, that may well change in the future.

The study also suffers from uncertainties that are caused by the limited number of radial velocities included in Gaia's second data release. Gaia's third data release, envisioned for 2021, should provide such information for a sample of stars ten times larger, which might help to identify additional candidates.

Another issue is 'Oumuamua's unknown age. The underlying analysis can only reasonably infer the stars' trajectories for the most recent few million years. If 'Oumuamua had been ejected during this period, there is a realistic chance that this study has identified its origin. If, on the other hand, 'Oumuamua is considerably older than this, it could have traversed a significant fraction of the Milky Way before reaching the Sun, meaning that, essentially, it will be impossible to ever identify its origin.

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Ramon Brasser (Tokyo Institute of Technology),
Marco Micheli (ESA SSA-NEO Coordination Centre),
Sukanya Chakrabarti (Rochester Institute of Technology),
Marc W. Buie (Southwest Research Institute),
Olivier R. Hainaut (ESO)

Coryn A. L. Bailer-Jones et al. 2018, "Plausible Home Stars of the Interstellar Object 'Oumuamua Found in Gaia DR2" in The Astronomical Journal, Vol. 156, 205. DOI: 10.3847/1538-3881/aae3eb

II.13 Highlights

A cold super-Earth in our neighborhood

An international group of astronomers, involving the Max Planck Institute for Astronomy (MPIA) in Heidelberg, has succeeded in detecting a planet around Barnard's star, which is only six lightyears away. The planet has just over three times the mass of Earth and is slightly colder than Saturn. The discovery was made possible by measuring the periodic change in the radial velocity of the parent star. The spectrograph CARMENES, developed to a large part by the MPIA, played an important role in this discovery.

Barnard's star (GJ 699) is the single star closest to Earth, located at a distance of 1.8 pc (about 6 lightyears). When viewed from the Earth, it moves faster than any other star in the sky. For a long time, the search for planets orbiting Barnard's star, a red dwarf star, had been unsuccessful. But finally astronomers have extracted a signal from 771 individual measurements collected over the past 20 years, which points to a planet that at a distance of 0.4 astronomical units (1 AU = 150 million km, the mean distance between the Sun and the Earth) travels around its host star once within 233 days. The planet has been named Barnard's star b (GJ 699 b). With a mass of at least 3.3 earth masses, it belongs to the class of super-Earths, i.e. exoplanets that fill the mass scale between the Earth and Neptune.

"For the analysis we used observations from seven different instruments spanning 20 years of measurements, making it one of the largest and most extensive datasets ever used for precise radial velocity studies", explained Ignasi Ribas of the Institut de Ciències de l'Espai (ICE, CSIC), Spain, and first author of the underlying research article.

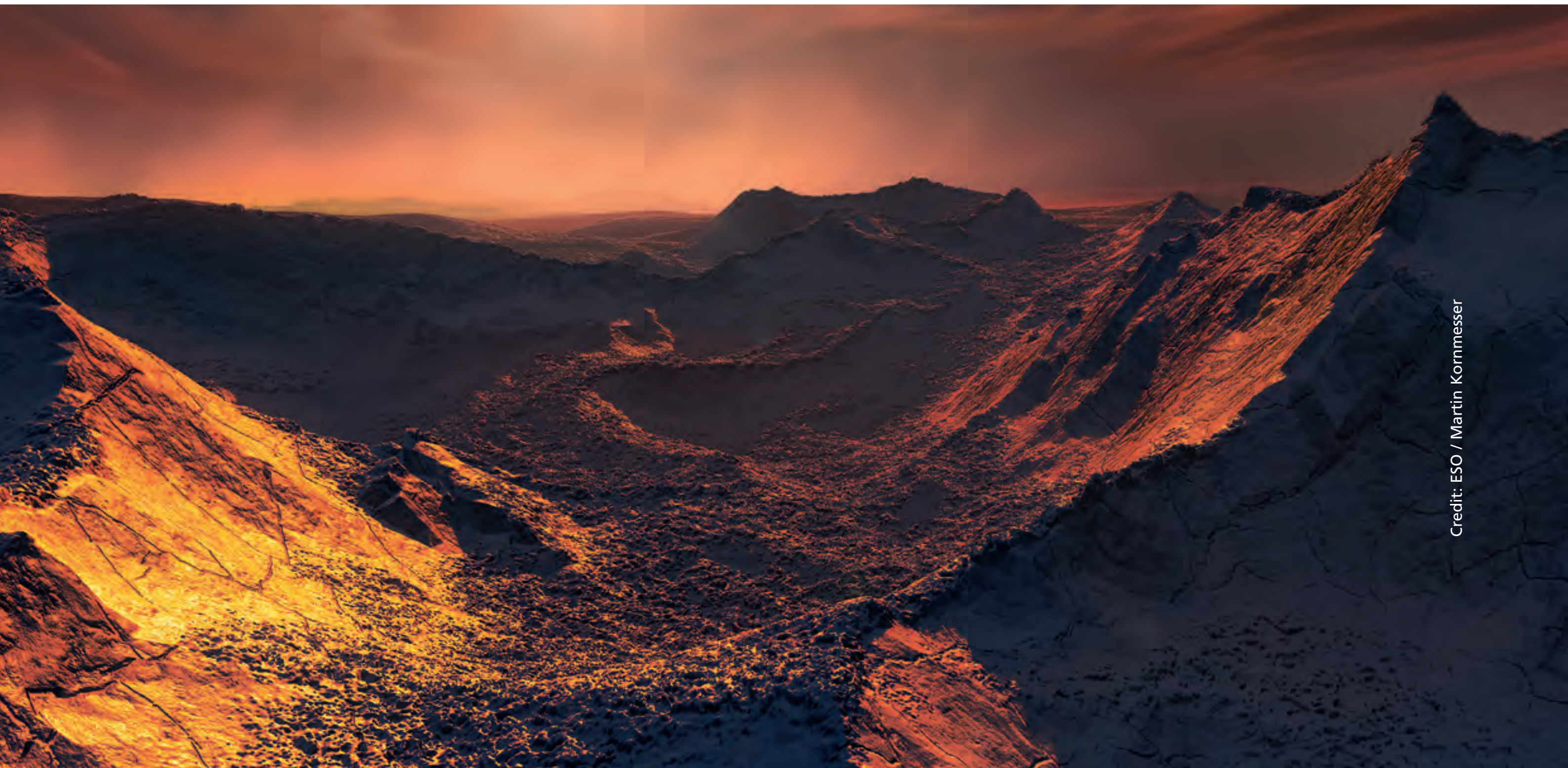
A cold inhospitable place

The planet lies almost exactly at the expected position of the so-called snow line of that system, a range in young planet forming systems where volatile compounds such as water freeze out inside the disk of dust and gas of which the planets are made, which is thought to be an important trigger for planet formation. It has long been suggested that this region might provide a favorable location for forming planets, with super-Earths being the most common type of planets formed around low-mass stars. Barnard's star b is to date the only low-mass exoplanet found orbiting near the snow line.

Barnard's star only emits 0.4 % of the Sun's radiant power. At its distance of 0.4 AU, the planet Barnard's starb roughly receives 2 % of the intensity the Earth collects from the Sun. From this, the scientists conclude that the planet with an average temperature of about −170 °C is probably a hostile, icy desert, in which there is no liquid water.

The discovery is based on the radial velocity method. Sensitive spectrographs register small periodic shifts of the spectral lines in the spectrum of a star due to its move-

Fig. II.13.1: Artist's impression of the surface on the planet Barnard's Star b.



Credit: ESO / Martin Kornmesser

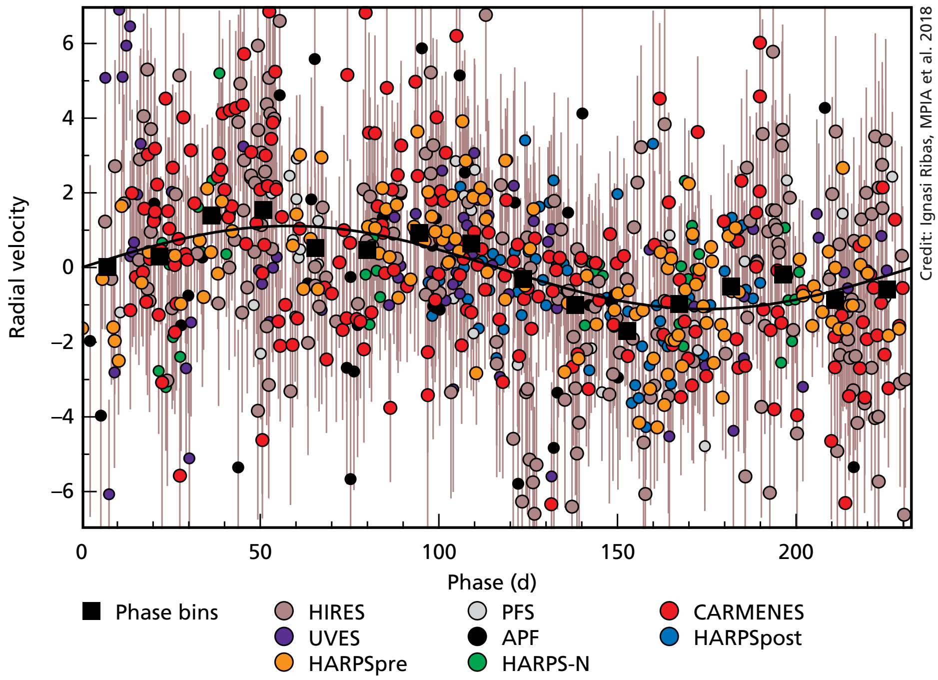


Fig. II.13.2: Phase-folded representation of the best-fitting 233-day circular orbit (*black line*) to the different datasets (*circles; see legend for colors indicating the different instruments*). The black squares represent the average velocity in 16 bins along the orbital phase.

ment along the line of sight caused by the planet pulling at its host star. From this the mass of the planet can be calculated. However, if the planetary orbit is inclined relative to the line of sight, we underestimate the change in velocity of the star and thus the mass of the planet. In most cases we do not know the inclination. Therefore, the 3.3 earth masses of Barnard's star b are only a lower estimate. However, they also represent the most probable value.

A result of many years of international cooperation

The data collected up to 2015 already contained indications of a planet. To this, MPIA astronomer Martin Kürster contributed 76 data sets from an earlier program at ESO's UVES spectrograph. However, certainty could only be obtained with additional measurements. Therefore, an international collaboration called "Red Dots" was formed to examine red dwarf stars such as Barnard's star in more detail employing the state-of-the-art spectrographs CARMENES, HARPS and HARPS-N. Precise spectrographs such as CARMENES, to whose development the MPIA has contributed significantly, enable astronomers to find increasingly smaller exoplanets that travel ever farther away from their stars.

Martin Kürster commented, "Until the 1980s, almost all professional and popular astronomy books stated that two Jupiter-like planets had been found near Barnard's star. This turned out to be incorrect following recent measurements in which I was partly involved. That is why it is all the more fascinating that we are now able to detect this planet with a much smaller mass".

Planetary systems in the Sun's neighborhood

In 2016 a planet was detected near the star that is closest to the Sun, Proxima Centauri. With Barnard's star b, we now know five planetary systems at a distance of up to 10 lightyears from the Solar System. Within a radius of 15 lightyears there are even 18 of these systems. Thus, the current discovery contributes to the perception that the formation of planets is apparently a very frequent cosmic phenomenon.

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in collaboration with

I. Ribas (IAC, Universidad de Laguna),
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Guillem Anglada-Escudé (Queen Mary University of London and Instituto de Astrofísica de Andalucía),
and the Pale Red Dot Collaboration

Ribas et al. 2018, "A candidate super-Earth planet orbiting near the snow line of Barnard's star" in Nature, Vol. 563, Issue 7731, pp. 365. DOI: 10.1038/s41586-018-0677-y

III. Instrumentation and Technology

Credit: Gerhard Hüdepohl, ESO

III.1 Overview

Instrumentation for Ground-based Astronomy

In 2018, MPIA activities in the area of ground-based instrumentation concentrated on spectroscopy, high fidelity imaging, and interferometric instruments for the telescopes VLT/VLTI and VISTA of the European Southern Observatory (ESO) and for the Large Binocular Telescope (LBT), survey instrumentation for Calar Alto. A new contribution to the 2.5 meter Nordic Optical Telescope on La Palma was started. MPIA's largest instrumentation projects consist of building two of the three first-light instruments for the Extremely Large Telescope (ELT), a next generation telescope with a main mirror of 39 meters in diameter.

Instrumentation for the Large Binocular Telescope (LBT)

The laser guide star system ARGOS for the Large Binocular Telescope (LBT) on Mount Graham in Arizona creates artificial reference stars on the night sky. These guide stars can be used with the two LUCI instruments: two near-infrared cryogenic imaging cameras and multi-object spectrographs that have been in operation at the LBT for several years, and have proven to be reliable workhorses for MPIA astronomers. For one side of the telescope, ARGOS had first light in 2015 and was commissioned until mid-2015, with major MPIA involvement, while for the other side it had first light in December 2015 and saw several commissioning runs in 2016 – 2018. At MPIA, the project was formally ended in December 2018, but the institute will continue to provide maintenance as needed.

The largest ongoing MPIA instrumentation project up to now is the near-infrared beam combiner LINC-NIRVANA (L-N). This instrument was finally installed at the LBT in late September 2016 and saw seven commissioning runs in 2017 – 2018, which will be continued in 2019. MPIA is the lead institute in the L-N consortium, which also includes the Italian Observatories (INAF), the Max Planck Institute for Radio Astronomy in Bonn, and the University of Cologne. The initial aim of the instrument is to deliver multi-conjugated adaptive optics imagery over a 10.5″ × 10.5″ field of view in the near-infrared regime at wavelengths between 1 and 2.4 micrometers. An optional future implementation step could provide diffraction-limited imaging with the spatial resolution of a 23 meter telescope. This would be achieved by coherent combination of light from the two LBT primary mirrors via Fizeau interferometry.

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

Instrumentation for ESO's VLT/VLTI and for the VISTA telescope

MPIA is participating in the second-generation projects MATISSE and GRAVITY for ESO's Very Large Telescope Interferometer (VLTI) at Paranal Observatory. VLTI combines multiple telescopes of the Very Large Telescope (VLT), namely different combinations of the 8.2 meter unit telescopes and the 1.8 meter auxiliary telescopes.

The MATISSE consortium consists of nine institutes led by the Observatoire de la Côte d'Azur. MATISSE combines the light from all four VLT unit telescopes in the mid-infrared for high spatial resolution image reconstruction on angular scales of 10 – 20 milliarcseconds. Scientific applications range from studies of Active Galactic Nuclei (AGN) to the formation of planetary systems and of massive stars, and the study of circumstellar environments. MATISSE was installed on Paranal in the fall of 2017, and most of the year 2018 was devoted to commissioning. MATISSE is now offered to the astronomical community for the observation period starting in April 2019, while additional commissioning activities will continue in parallel.

GRAVITY also combines the light of the four VLT unit telescopes, but in the near-infrared. The GRAVITY consortium is led by the Max Planck Institute for Extraterrestrial Physics in Garching. The partners include MPIA, the observatories in Paris and Grenoble, and the Universities of Cologne and of Lisbon. Assisted by a high-performance adaptive optics system, GRAVITY provides precision narrow-angle astrometry and phase referenced imaging of faint objects over a field of view of 2″.

GRAVITY has been offered to the astronomical community together with MPIA's main contribution, the four wavefront sensor systems CIAO (short for Coudé Infrared Adaptive Optics), since the fall of 2017.

Applications of GRAVITY include the study of motions close to the massive black hole in the Galactic Center, the direct detection of intermediate-mass black holes in the Milky Way galaxy, dynamical mass determinations of extrasolar planets, the origin of protostellar jets, and the imaging of stars and gas in obscured regions of active galactic nuclei (AGN), star forming regions, or protoplanetary disks.

In particular, GRAVITY observed the S2 object near the Galactic Center in 2017 and 2018 when the object is at its closest approach to the black hole in the Galactic Center. This has already permitted researchers to test and confirm general relativity under extreme conditions of strong gravity (see the science highlight II.11). In December 2018 the project was formally ended at MPIA.

The project 4MOST, which MPIA joined in 2014, is a multi-object spectrograph for the 4.1 meter VISTA telescope at ESO's Paranal observatory. In April 2018, it passed the major part of its Final Design Review, with a second part scheduled for Januar 2019. After that, MPIA will deliver its contributions to the partner institutes in 2019. The project is led by the Astrophysical Institute Potsdam. MPIA is responsible for the instrument control electronics. The instrument is supposed to study the origin of the Milky Way and its chemical and kinematic substructure, as well as the evolution of galaxies. To this end it will employ 2400 fibres over a field of view of 4 square degrees, enabling simultaneous spectrography of up to 2400 different objects within the field of view.

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

MPIA's formal involvement in the Calar Alto Observatory has come to an end in December 2018. Throughout 2018, MPIA has been cooperating with Calar Alto in the framework of an upgrade of the PANIC instrument and 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 about mid-2020.

Fig. III.1.1: Construction work has commenced for the Extremely Large Telescope on Cerro Armazones in Chile, seen here as of December 2018.

The Panoramic Near-Infrared Camera (PANIC), operational between April 2015 and mid-2018, is a wide-field general purpose instrument for the CAHA 2.2 meter telescope and a joint development of the MPIA and the Instituto de Astrofísica de Andalucía. Originally, with four Hawaii2-RG detectors, it provided a field of view of 30′ × 30′ (corresponding to the apparent size of the full moon in the sky), allowing for surveys of extragalactic, galactic, and Solar System objects. Upon relocating the instrument back to MPIA in August 2018, we commenced a refurbishment project of replacing its detector mosaic by a better quality single Hawaii4-RG detector that will cover the same field of view, which will be finished in 2019. Reinstallation on Calar Alto and commissioning are foreseen for early 2020.

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 buildt by a consortium of five German and six Spanish institutions. With 750 guaranteed observing nights available 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. By the end of 2018, a little over 50 % of the guaranteed time was used up; the remaining observations will be carried out until mid-2020.

In December 2019, a memorandum of Understanding was signed 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 will contribute three systems of its in-house developed read-out electronics and software to this project and characterize the infrared detectors. NTE is slated for installation at the NOT in late 2020.

Fig. III.1.2: Artist's impression of the completed Extremely Large Telescope on Cerro Armazones in Chile.

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 (Fig. III.1.1).

MPIA participates in two of the three first-light instrumentation projects: METIS and MICADO (see chapter III.3 for an overview of MICADO). In 2018, both MICADO and METIS were in their preliminary design phases with MICADO passing its review in November and METIS slated to pass review in May 2019, respectively. The subsequent final design phases will last until October 2020 for MICADO and until May 2021 for METIS.

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

MICADO is a near-infrared imaging camera with multi-conjugated adaptive optics that will provide spatial resolution exceeding that of the James Webb Space Telescope (JWST, the successor to the Hubble Space Telescope) by a factor between 6 and 7. 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.

Martin Kürster for the MPIA Technical Departments

III.2 Overview

Instrumentation for Space-based Astronomy: Euclid

Space-based telescopes play an important part in the observations performed by astronomers at the Max Planck Institute for Astronomy. For decades, the institute has also been active in contributing instrumentation to space missions, mostly in the area of infrared astronomy, as for ESA's Herschel mission as well as for the NASA/ESA James Webb Space Telescope, slated for launch in 2022. In the following, we concentrate on our contributions to ESA's Euclid mission.

ESA's Euclid mission is set to launch in mid 2022 as astronomy's prime probe for the nature of dark matter and dark energy. Euclid will utilize high-fidelity imaging and spectroscopy in the visual and near-infrared wavelength ranges to measure distance, spatial distribution and shape of a billion galaxies over nearly half the sky. Its goal is to measure the evolution of cosmic expansion and the distribution of dark matter across cosmic time from 10 billion years in the past (redshift $z = 2$) to today.

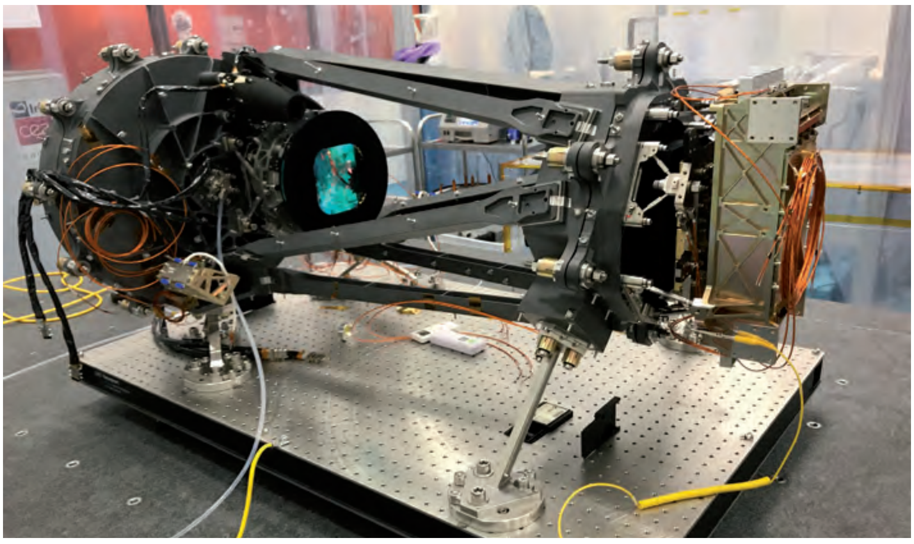
Hardware for a cosmological mission

In 2018 MPIA completed its hardware contribution to NISP, the France-led near-infrared imaging and spectroscopy instrument onboard Euclid. The same is true for most of NISP's other components, the mechanical structure, optics, electronics, and detector system. NISP engineers have by now assembled most of the Flight Model in the clean-room at LAM Marseille (Fig. III.2.1).

Two hardware components are provided by MPIA: near-infrared filters that provide the instrument with three distinct photometric band-passes between 950 nm and 2000 nm, and a calibration light source featuring LED illumination at five wavelengths in the same range, both funded by the German national aerospace agency DLR.

The filters are made of high-transmittance Zerodur 3001 glass blanks of 170 mm diameter and were coated with bandpass-defining interference coating at Optics Balzers Jena. These are the largest near-infrared filters ever to be used in space up to the mid 2020s – at least for astronomy. Mid 2018, the filters were brought to Barcelona and inserted into the Spain-led filter wheel, tested and delivered to LAM for integration into the NISP Flight Model (Fig. III.2.2). A backup set of filters was also delivered, and is now included in a Flight Spare filter wheel, manufactured in parallel in case of any issue with the nominal Flight Model. Some final characterization of the band-passes is still being carried out in Jena to provide a high-fidelity bandpass definition for all scientific analyses of the NISP data later on.

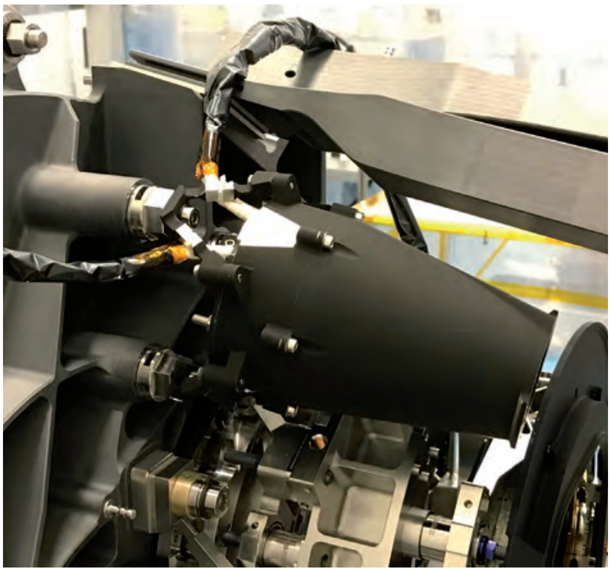
Fig. III.2.1: Completely assembled Euclid NISP Flight Model in the LAM cleanroom. This instrument model will be put through vibration and thermal vacuum tests and receive a full characterization of its optical and detector properties before being delivered to ESA at the end of 2019, and launched as part of Euclid in 2022.



Credit: NISP Team

Credit: NISP Team

Fig. III.2.2: Final NISP photometric filter wheel in the process of being mounted inside the Flight Model. The wheel provides a closed shutter position (*black, right*), an open position, and three bandpass filters (*left top and bottom, right*). These only transmit light in the near-infrared and appear as mirrors in visible light, as in this picture, where the engineers are actually seen in reflection.



Credit: NISP Team

Fig. III.2.3: NISP calibration lamp NI-CU, provided by MPIA, as mounted in its final position on the NISP Flight Model. Clearly visible are the nominal and redundent harnesses, the cables providing power and diagnostic capabilities to the 2 x 5 LEDs inside the lamp.

Calibration: LEDs in space

MPIA's second hardware contribution is a near-infrared calibration lamp that has been designed and built near Heidelberg under MPIA supervision. Five different LED types were constructed and qualified for this purpose, allowing the lamp to illuminate the NISP detector array with a highly stable amount of light at five different wavelengths, which in turn allows us to calibrate the detector's sensitivity. The Flight Model and Spare of this light source were fully built, tested, and delivered to Marseille in 2018 as well. The lamp has now also been integrated into the NISP Flight Model (Fig. III.2.3) and will be used both in the upcoming ground-based NISP thermal vacuum tests and NISP detector characterization, as well as throughout the 6.5 year Euclid survey.

From hardware to science

Aside from hardware MPIA has further central functions inside the NISP instrument development group: photometry instrument scientist, calibration lead, instrument simulator. Here MPIA provided central input to understanding the actual properties of NISP versus its requirements, e.g. in limiting sensitivity and calibration uncertainty, including contributions to testing of instrument before and after coupling with the telescope.

Overall, MPIA's hardware activities for Euclid have been completed in 2018, and will now be restricted to support during tests at LAM. NISP overall is now following its schedule for full completion and characterization, to be delivered to ESA at the end of 2019 and subsequently integrated into Euclid's payload module the year after.

MPIA's involvement in Euclid will not stop there. It will shift more towards contributions to the computing ground segment, after launch to operating NISP and assessing its performance, and beyond that to science exploitation of the vast and unprecedented dataset. This will include highly interesting analyses outside the mission's nominal main science goals: With a substantial high spatial-resolution visible imaging dataset (0.1 arcseconds) and deep infrared data (signal-to-noise ratio S/N = 5 for point sources at magnitude 24) for over a third of the sky, the possible science applications are vast, ranging from observational studies of galaxy evolution and maybe even to the discovery and characterization of exoplanets.

Knud Jahnke for the Euclid Group

III.3 Overview

MICADO – near-infrared first light instrument for the Extremely Large Telescope

MICADO (Multi-AO Imaging Camera for Deep Observations) is one of the three first light instruments being built for the Extremely Large Telescope of the European Southern Observatory. The instrument will offer multiple imaging and spectroscopic observing modes in the near infrared wavelength region (0.8 µm – 2.4 µm), with focus on high resolution and sensitivity.

The ELT will be the largest optical telescope ever built, with a main mirror diameter of 39 m. MICADO is designed to make use of the unique properties that such a giant telescope offers. Fig. III.3.1 shows the gravity-invariant orientation of the 16 ton instrument on the Nasmyth platform with respect to the telescope.

The main goal of the project is diffraction limited imaging, which is enabled by a single-conjugate adaptive optics (SCAO) system during the so-called standalone operation mode. To allow for diffraction limited 53 arcsec wide-field imaging, MICADO will be supported by the multi-conjugate adaptive optics module MAORY, which is built by another consortium. In conjunctions with these AO systems, a resolution of 5 – 12 mas (FWHM) in the J-K bands will be achieved, which is five to six times better than what can be achieved with the 8 m class Very Large Telescope (VLT), or even the James-Webb Space telescope.

To enable stable high precision astrometry, the whole instrument is constructed in a gravity-invariant fashion and only rotated around the vertical axis, to avoid flexure effects. Other observing modes of the instrument are long-slit echelle spectroscopy with intermediate spectral resolution ($R \sim 15{,}000$), and coronagraphy to resolve nearby planets in direct imaging.

In order to reduce thermal background radiation, most parts of the instrument are located in a large cryostat and cooled to cryogenic temperatures of about 77 K. Fig. III.3.2 shows a schematic view of the internal optical concept. After the light passes a field stop wheel, a collimator and a filter wheel, the so-called main mechanism allows astronomers to switch between the different observing modes. In the end, the light is focused on a detector array which consists of 9 of the newest HAWAII-4RG detectors (each with a 4096 pxl × 4096 pxl CCD, and with two pixel scales: 1.5 and 4 mas per pixel).

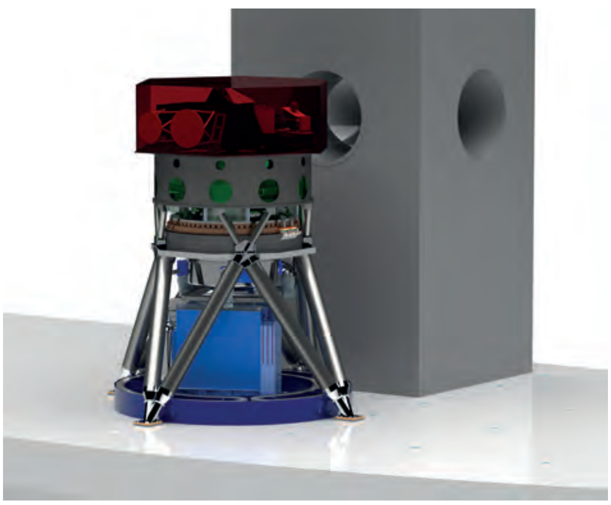
With its different modes, MICADO is a versatile instrument suitable for a variety of science cases. The high astrometric precision, for example, will allow researchers to study proper motion of stars both in the center of the Milky Way and in other nearby galaxies at an unprecedented combination of angular resolution and up to 20 µas accuracy, in order to probe the gravitational potential in crowded cores of star clusters and galactic nuclei. MICADO astrometry will search for intermediate mass black holes and central dark matter distributions.

MICADO is designed and built by an international consortium with institutions from 5 countries. The project is led by the Max-Planck-Institute for Extraterrestrial Physics (MPE) in Garching. The MPIA is responsible for the instrument derotator, the calibration unit, and the overall astrometric performance.

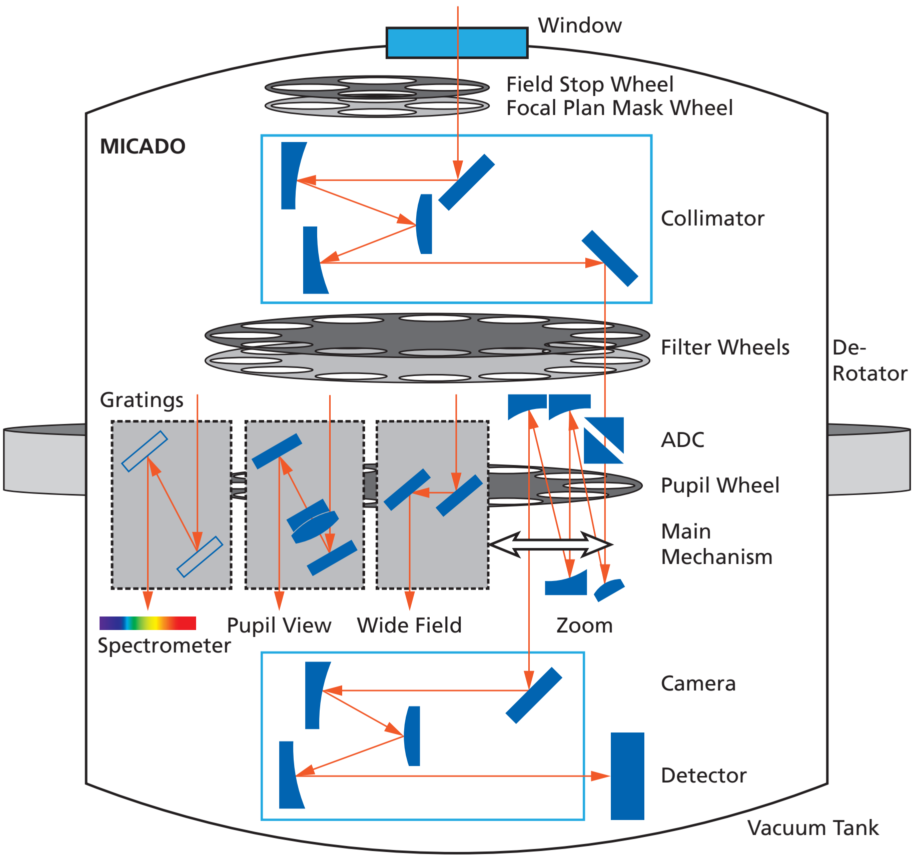
The preliminary design phase of the instrument ended with a successful preliminary design review (PDR) by ESO and several external experts, which was held in November 2018. The project now approaches its next milestone during the so-called final design phase (often called Phase C), which is currently expected to be concluded with a review in October 2020.

Following the PDR, and the parallel development of the interfaces to the ELT and MAORY, some work packages were rearranged. The MPIA is responsible for the calibration unit, and the overall astrometric performance. This includes now the warm relay optics, the optical interface between the ELT and the MICADO

Fig. III.3.1: Illustration of MICADO stand alone on the ELT Nasmyth platform. Inside a fixed structure, the cryostat and wavefront sensors will be rotated by the MPIA built derotator to the extreme derotation precision of 2 arcsec. The light of the telescope enters the cryostat from above.



Credit: MICADO consortium



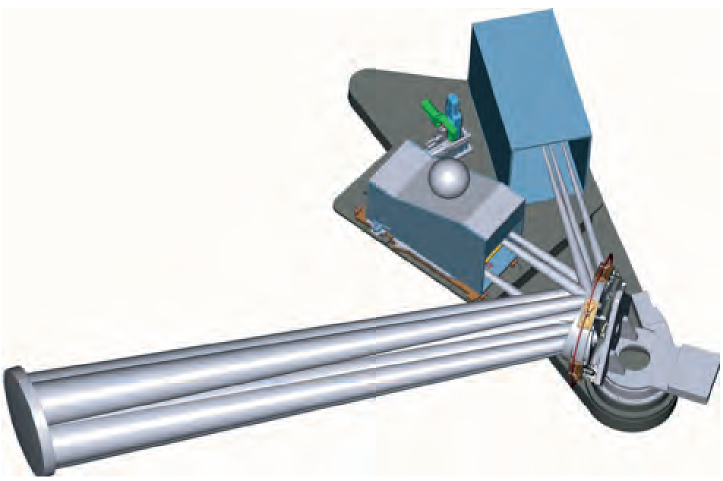
Credit: Richard Davies et al. 2016

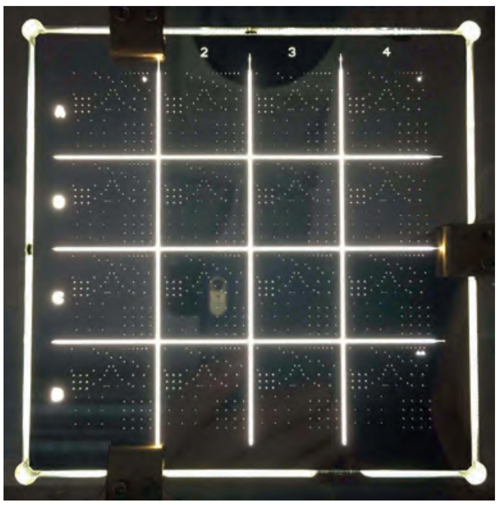
Fig. III.3.2: Schematic view of the optical components of the MICADO cryostat.

cryostat, which will be designed, and tested at MPIA, and allow for first light operation of MICADO at the ELT without the full MAORY. MPIA also developed a high performance instrument derotator concept (see below).

Since ELT diffraction limited imaging is essentially aiming for five times better (finer) resolution with telescope that is five times bigger compared to the existing 8 m class telescopes, the relative accuracies of smallest versus largest scale are five times tighter. Unfortunately, an additional complication is that these accuracies are harder to achieve since at ELT scale, thermal gradients and flexure provide for a continuous drift. Thus, precise

Fig. III.3.3: *Left:* MCA overview, three units to fulfill flat-field and wavelength, movable source and astrometric calibrations. The light from the MCA subunits is conveyed to the instrument through a steering mirror that redirects the light to the instrument during the calibration run. *Right:* prototype of the MICADO astrometric mask tested at MPIA and backside illuminated to deliver multiple reference points for the mapping of the instrument distortions.





Credit: Gabriele Rodeghiero, Jörg-Uwe Pott, Norbert Münch, Ralf-Rainer Rohloff, Ulrich Grözinger, et al.

calibration and position encoding are challenges for any ELT instrument, and MPIA is at the center of this development with its MICADO workpackages, described in the following.

The MICADO Calibration Assembly

The MICADO Calibration Assembly (MCA, Fig. III.3.3 left) provides multiple calibration functionalities to the instrument. For one, it delivers a uniform illumination of the MICADO focal plane (flat-field) and supplies several calibration light sources (gas lamps) for its spectrograph. The unit also contains an astrometric calibration mask for mapping the optical distortion of the instrument, which is fundamental for the correction of the observed tiny star motions. A movable point-like light source provides a reference for the calibration of the adaptive optics wavefront sensor as well as for alignment purposes.

In 2018, many prototype components of the MCA have been realized and tested at MPIA, in order to verify their technological readiness level. One critical component is the astrometric mask (Fig. III.3.3 right) that needs to be manufactured and to remain stable at a nanometer level in order to provide a suitably accurate reference for the astrometry of the instrument. An extended measurement campaign has managed to measure the position of the reference points on the mask with a precision of 50 nm/1 mm, which is equivalent to the MICADO astrometric requirement of measuring the position of a star with 50 μas precision in a one arcsec field of view.

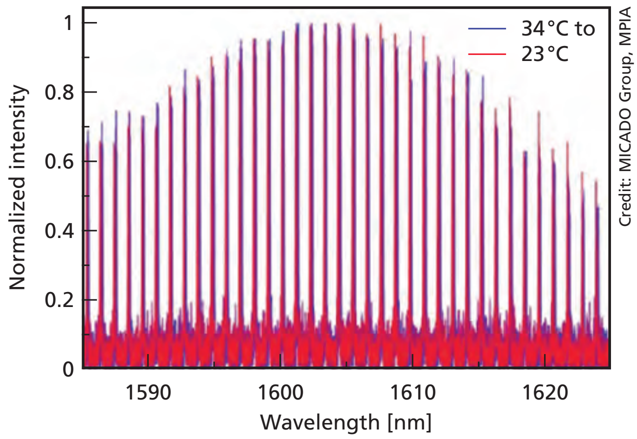


Fig. III.3.4: Measured spectrum from the prototype Fabry-Pérot under test at MPIA. A major concern of this device is its wavelength stability against temperature drifts.

Another important piece of the puzzle that is the MICADO calibration has been achieved with the procurement and test of a Fabry-Pérot etalon, which provides an equally spaced and regular pattern of reference lines for the spectrograph calibration (Fig. III.3.4). The wavelength calibration is particularly critical in the near infrared region around and beyond 2 μm, due to the intrinsic lack of natural calibration lines from the gas lamps in this region. In this context, the use of a Fabry-Pérot significantly improves the calibration capabilities, but it requires careful thermal stabilization of the device in order to avoid drifts in the line position.

Fig. III.3.5: CAD model of the MICADO derotator preliminary design with the main subsystems.

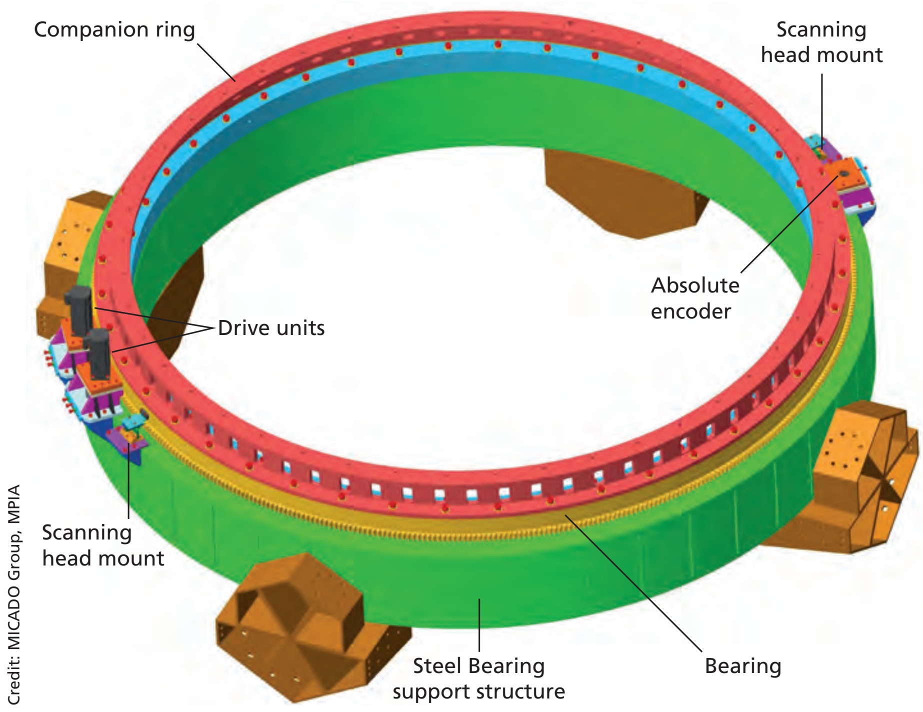


Fig. III.3.6: The derotator test stand completely assembled and under test at MPIA labs.

MICADO Derotator PDR Concept

MPIA was responsible for the developmen and prototyping of the MICADO derotator concept. The ELT's alt-azimuth mounting induces a field rotation of the sky as seen through the instrument. In order to counteract this motion, the cryostat needs to rotate in the opposite direction. The object which provides this functionality is called a derotator, and it is shown in Fig. III.3.5. The biggest challenge of the system is achieving a relative angular positioning accuracy lower than 2 arcsec while the telescope tracks the scientific target, in order to minimize the astrometric errors of MICADO.

The preliminary design of the derotator is based on a ball bearing, a companion ring and a bearing support structure made of steel. The work package comprises the design elaboration, manufacture and verification of the derotator with a half-scale test stand prototype. The derotator prototype test bench includes a ball bearing, a support structure and a dummy unit simulating the MICADO cryostat mass. The test bench allows also for testing the alignment and drive system, the positioning measurement system, the friction simulator and the control electronics to operate the derotator in closed-loop (Fig. III.3.6). The measured relative angular positioning accuracy of the derotator prototype over the whole range of field rotation at the velocities expected for MICADO is at the level of 0.65 arcsec, so well within specification.

MICADO warm relay optics

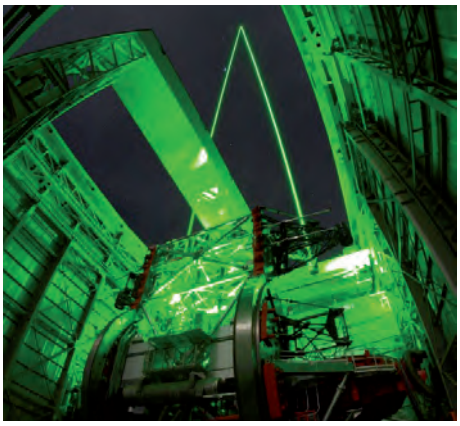
After finishing the derotator PDF study, we took the responsability of the design and development of the complete opto-mechatronics of the warm relay optics, 6 large-scale (10s of centimeter) high-precision optics, which relay the scientific field from the ELT focus into the cryostat. These optical elements allow for early scientific operation in SCAO mode (adaptive optics with a single guide star), while the more sophisticated MCAO modes (with multiple guide stars) are still in development. In this way, MPIA's instrumentation developments will literally support mankind's first gaze through the giant eye of an extremely large telescope.

Jörg-Uwe Pott, Maximilian Häberle,
Gabriele Rodeghiero and Santiago Barboza
for the MPIA-MICADO Team

III.4 Instrumentation at MPIA

Overview of current projects

Astronomical instruments have different strengths and specializations. Here, we list **ongoing MPIA instrumentation projects for the year 2018.** Almost all of the instruments are cameras for producing astronomical images, spectrographs for analyzing the color components of light, or combinations thereof. The only exception is ARGOS, which enables another pair of instruments to take sharp images by projecting artificial laser stars into the sky.



ARGOS

Advanced Rayleigh guided Ground layer adaptive Optics System

Telescope	Large Binocular Telescope, Mt. Graham
Wavelength range	–
Targets	–
Resolution	–
Special features	–
MPIA contribution	Testing, control software / motor control, calibration, alignment
Status	Binocular operation mode using both LUCIs achieved

LINC-NIRVANA

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

Telescope	Large Binocular Telescope, Mt. Graham
Wavelength range	Near-infrared, 1.1 – 2.4 µm
Targets	Star clusters, black holes, protoplanetary disks
Resolution	30–90mas (wavelength-dependent); interferometric: 10–30mas
Special features	Particularly wide-field adaptive optics
MPIA contribution	PI institute, project lead; optics, electronics, software
Status	Advanced commissioning phase

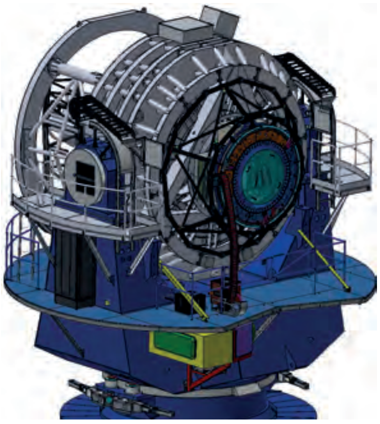
MATISSE

Multi AperTure mid-infrared SpectroScopic Experiment

Telescope	Very Large Telescope, Paranal, Chile
Wavelength range	Mid-infrared (3 – 25 µm = L, M, N bands)
Targets	Active galactic nuclei, protoplanetary disks, hot / evolved stars
Resolution	3 – 26 mas depending on wavelength and telescope baselines
Special features	Image reconstruction from interferometric data
MPIA contribution	Integration cryostats with cold optics / detectors, electronics / tests
Status	Advanced commissioning phase, start of operations in April 2019

GRAVITY

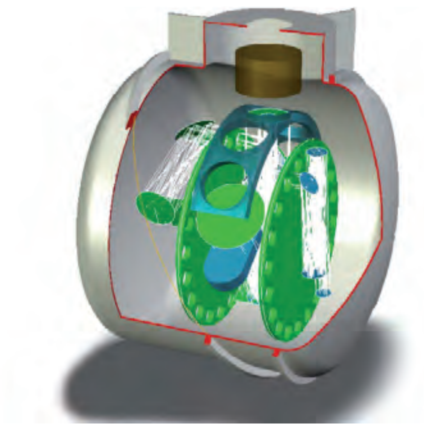
Telescope	Very Large Telescope, Paranal, Chile
Wavelength range	Near-infrared, 2.2 µm
Targets	Milky Way black hole, planets, brown dwarfs, disks / jets, AGN
Resolution	4 mas for imaging
Special features	High-precision narrow-angle astrometry down to 10 mas
MPIA contribution	Four wavefront sensors for the AO system
Status	All four AO units built at MPIA operational at VLT



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
Status	Final design review passed



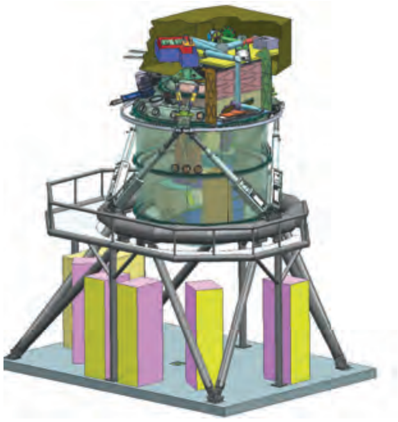
MICADO

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	instrument derotator bearing, astrometric calibration
Status	Preliminary design review passed

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

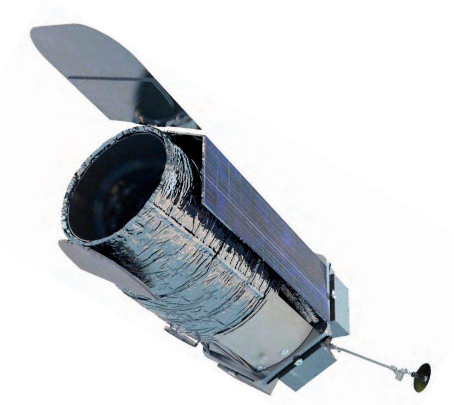
Astronomical objects are extremely distant, making it difficult to discern any details. The **resolution** is a measure of the level of detail that can be achieved using a particular instrument. Resolution is given as an angle on the sky: a resolution of 0.1 arcseconds means that, say, an astronomical camera can distinguish two small objects that are 0.1 arcseconds (less than 0.00003 of a degree) apart on the sky. Resolution is typically given in arcseconds (1 arcsecond = 1/3600 of a degree) or even milli-arcseconds, mas (1 mas = 1/1000 arcsecond).



METIS

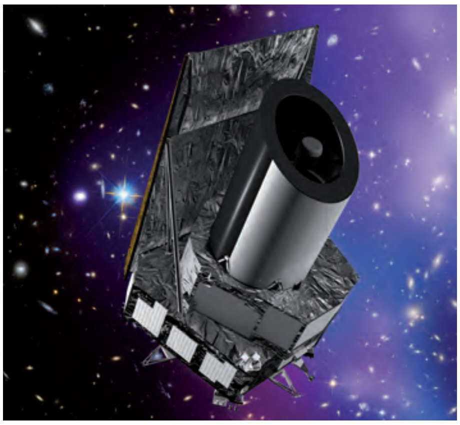
Mid-infrared ELT Imager and Spectrograph

Telescope	Extremely Large Telescope
Wavelength range	Mid-infrared (3 – 9 µm = L/M, N, Q bands)
Targets	Disks, exoplanets, supermassive black holes, high-*z* galaxies
Resolution	16 – 74 mas depending on wavelength
Special features	Can do coronagraphy and polarimetry
MPIA contribution	Imager and single-conjugate adaptive optics
Status	Preliminary design phase



WFIRST

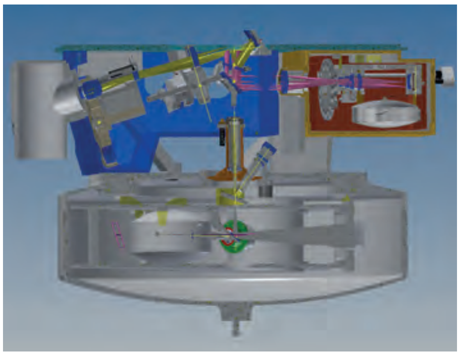
Telescope	WFIRST denotes the whole space telescope
Wavelength range	Near-infrared, large region imaging
Targets	Exoplanet detection and dark energy research
Resolution	Wide field near-infrared imaging with an angular resolution of ~ 0.2 arcsec
Special features	Field-of-view 100 times that of the HST; coronagraphs
MPIA contribution	Mechanisms and their control for ground support equipment
Status	Phase B



EUCLID

Telescope	Euclid denotes the whole space telescope
Wavelength range	Visible light, 0.5 – 0.9 µm, and infrared light, 0.965 – 2.0 µm
Targets	Tracing cosmic large-scale structure and cosmic acceleration
Resolution	86 – 344 mas depending on wavelength
Special features	Galaxy morphology, IR photometric redshifts and spectroscopy
MPIA contribution	Infrared detector calibration unit, near-infrared photometric filters, data simulations, calibration coordination
Status	Flight models completed and delivered; testing and characterization of NISP instrument and telescope in 2019–2021

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.



NTE

NOT Transient Explorer

Telescope	2.5 meter Nordic Optical Telescope (NOT), La Palma
Wavelength range	UV, visible, near-infrared, 334 – 2200 nm
Targets	Transient phenomena, gamma-ray bursts, gravitational wave sources, kilo- and supernovae
Resolution	Imaging: 0.18″/pixel, field-of-view 6′; spectroscopy: $R \sim 5000$; 20″ long slit
Special features	Rapid resonse mode (< 2 minutes) under development
MPIA contribution	Read-out systems for the NIR cameras
Status	Interfaces defined, Memorandum of Understanding signed, manufacture of MPIA contributions started

PANIC-4K

PAnoramic Near-Infrared Camera with a 4K detector

Telescope	2.2 meter Telescope, Calar Alto
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	Integration and characterization of new HAWAII-4-RG detector
Status	Ready for integration upon delivery of detector

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.

III.5 Highlight

Technical Departments

Highlights from MPIA's Technical Departments were the opening of a new optics lab for precision measurements and the development of new coatings for carbon fiber reinforced plastics as an innovative material for building astronomical instruments.

Observational astronomy places high demands on its tools: telescopes and instruments. New astronomical instruments are almost invariably custom developments, the result of cooperation between the researchers themselves, institute engineers and partners in industry. Designing and building such instruments – from highly sensitive imagers to spectrographs – has a long tradition at MPIA, which boasts a dedicated community of scientists, engineers and technicians.

MPIA's technical departments comprise the engineering design department, the precision mechanics workshop, and the electronics, software, and instrumentation departments. These departments with their workshops and design offices participate in the development and construction of cutting-edge astronomical instruments which are then deployed at sites such as Calar Alto Observatory, the telescopes of the European Southern Observatory (ESO), the Large Binocular Telescope, or aboard ESA or NASA space telescopes.

Credit: MPIA

Fig. III.5.2: Optics designer Conchi Cárdenas Vázquez with the "ZYGO dynafiz" interferometer, which allows for vibration-insensitive measurements.

Optics Lab 002

This year, a new optics lab was established at MPIA in order to support instrumentation projects. The new lab features highly sensitive optical measurement setups and a clean environment that is compliant with the high standards set for space projects. The main focus for this laboratory is on interferometric setups. The key piece of

Fig. III.5.1: The new Optics Lab 002, with clean room area for handling final hardware under controlled environmental conditions.

Credit: MPIA

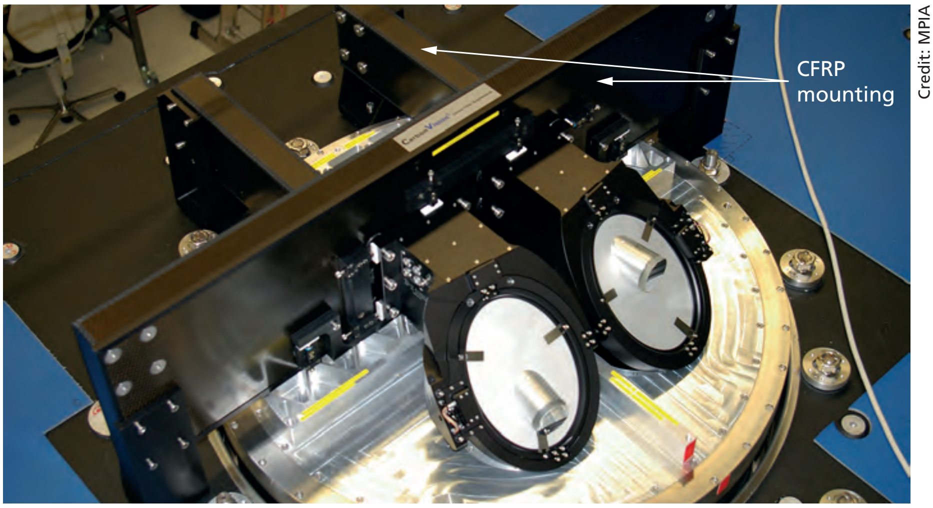


Fig. III.5.3: Structural components made of CFRP in the LBT instrument LINC-NIRVANA.

equipment is a vibration insensitive interferometer, which allows for measurements inside cryostats at cold conditions. Conventional interferometers, auto-collimation telescopes, wave-front sensors and machine vision systems found a home in this controlled environment as well. A cleanroom area with class ISO 6 allows the operation of final hardware under temperature-stabilized conditions.

Functional layers on carbon fiber reinforced plastics

Carbon fiber reinforced plastics (CFRP) have also become established in astronomical instrument building. Especially in applications where high stiffness of low-mass components, low thermal strain and good damping properties are required, CFRP is a better choice than steel or aluminum. Fig. III.5.1 shows an application in the instrument LINC-NIRVANA at the Large Binocular Telescope (LBT).

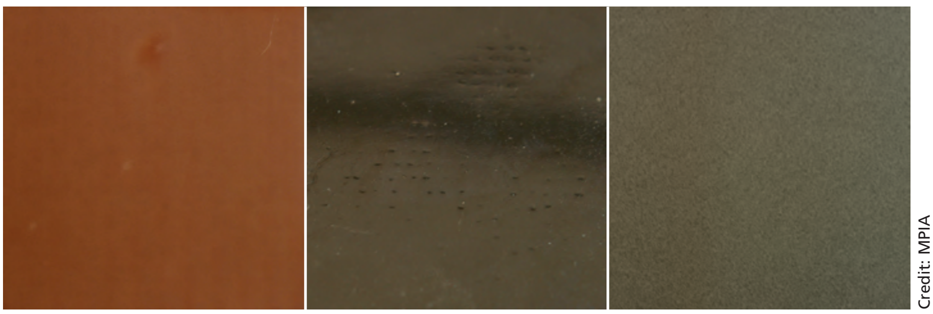
In order to expand the range of applications of this material, MPIA has carried out coating tests in cooperation with various institutes and companies. Fig. III.5.4 shows at left a sample coated with copper by "cold plasma spraying". An important requirement is that a very good connection of the copper layer to the CFRP surface must be ensured. For this, the material must be pretreated accordingly.

Copper may also serve as the starting metallization for other functional layers (e.g., electroless nickel, see Fig. III.5.4, center). Metallized CFRP components can thus also be used without hesitation in vacuum at problematic locations (protection against outgassing) or can be reworked after coating with machining production processes.

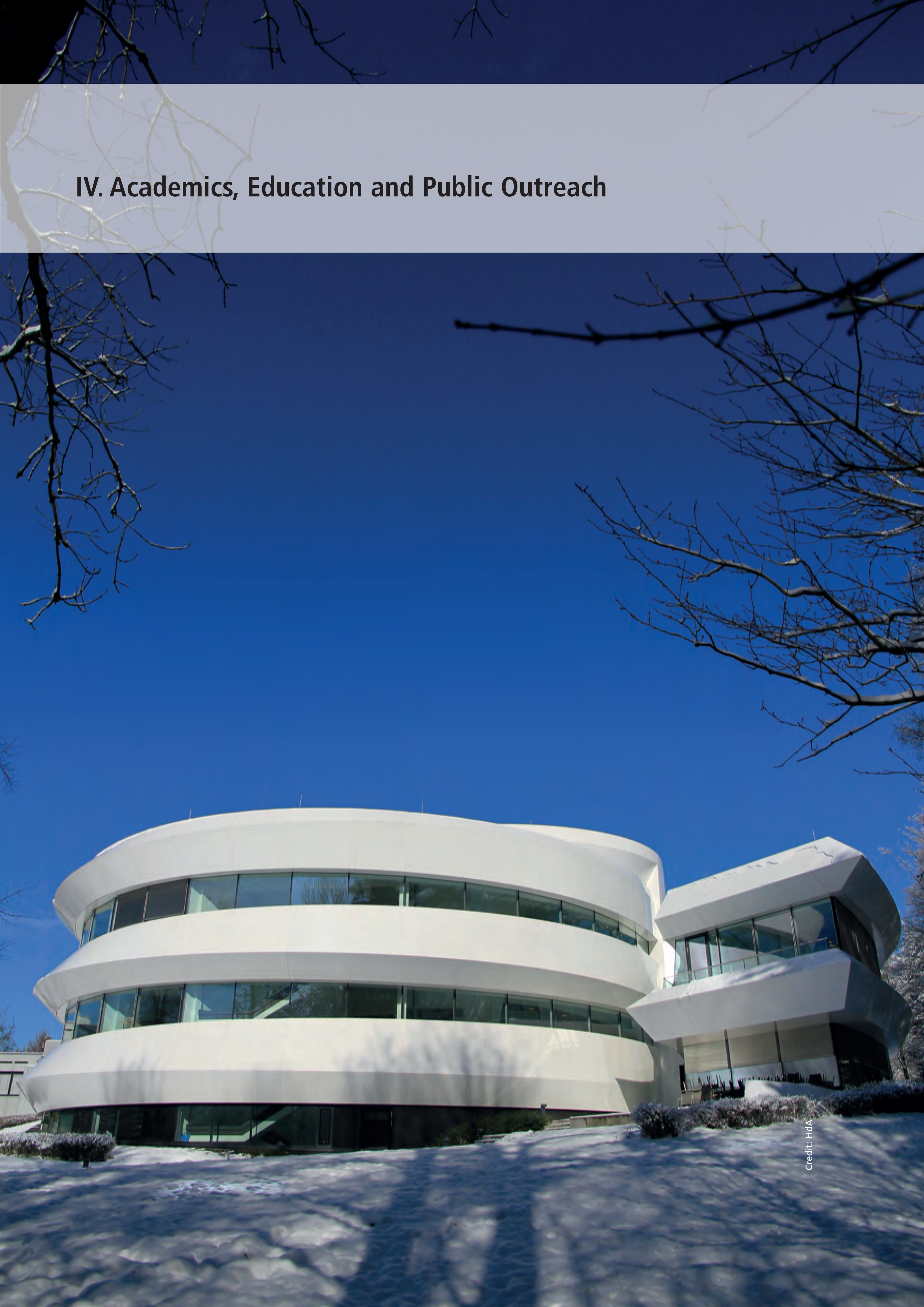
Also, ceramic layers (see Fig. III.5.4, right) are feasible, allowing for increased wear protection or very good laser resistance. Special coatings on CFRP open up extended fields of application and new, interesting component properties. Further experiments are planned in the future.

Martin Kürster, Peter Bizenberger and Ralf-Rainer Rohloff for the MPIA Technical Departments

Fig. III.5.4: *Left:* CFRP plate coated with copper (cold plasma spraying). *Center:* CFRP plate coated with copper and electroless nickel (NiP). *Right:* CFRP plate coated with a ceramic layer.



IV. Academics, Education and Public Outreach



Credit: HdA

IV.1 Overview

Academics

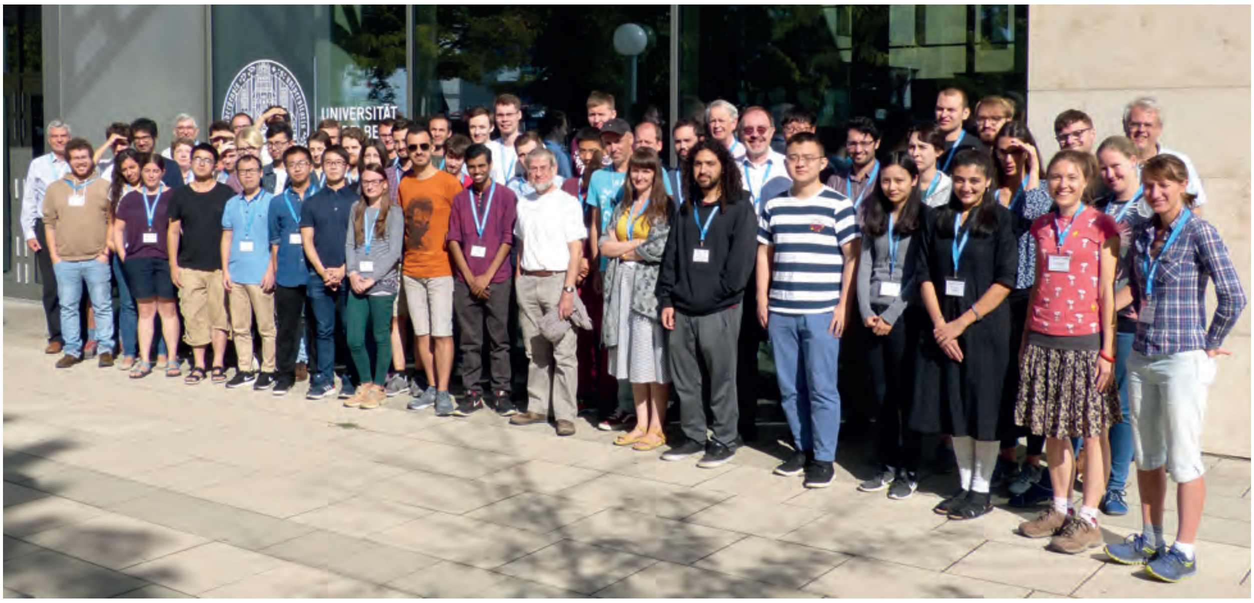
As a research institute, MPIA takes its responsibility for fostering future generations of scientists seriously. Our involvement begins at the undergraduate level. The directors, the research group leaders and the PhD students are involved in teaching at Heidelberg University. For example, this year MPIA scientists were involved in teaching the Galactic and Extragalactic Astronomy Block Course (Nadine Neumayer), as well as a lab course on numerical methods (Hubert Klahr), and seminars on topics as diverse as the physics of star formation (Thomas Henning) and stellar atmospheres (Maria Bergemann and Karin Lind). The PhD students typically work as tutors for introductory physics courses and for the astronomy and astrophysics lab courses. 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 Bertrand Goldman).

A key part of MPIA's educational efforts is the training of doctoral students. For this, the International Max Planck Research School for Astronomy & Cosmic Physics at the University of Heidelberg (IMPRS-HD) plays a central role – not only for MPIA, but also for 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 at the IMPRS seminars and retreats, offers help with everyday administrative problems, and also offers a social network, in particular for foreign students.

The year 2018 of the IMPRS-HD is the school's 14th year of activity. It saw the 14th generation of IMPRS taking up their studies; a generation that, in particular due to the positive funding situation (the extension of the SFB 881 was granted 2018) is exceptionally strong, comprising 27 new PhD students have started. Of those, 17 are of non-German citizenship, 9 are female, and 14 are located at MPIA. Of particular note is the high number of Chilean students (4) and the 2nd (since 2005) French student. Since the first IMPRS generation in 2005, a total 366 PhD students have started their studies in this framework. Of those, 247 had graduated by the end of 2018. The steady-state number of IMPRS students continued to be of the order of 90.

It is expected that these numbers will change during the next years. The reason is the increase of the PhD salaries to about 65 % (including a "Gewinnungszulage" hiring bonus) of a postdoc salary. This has been decided within MPIA after extensive discussions with the student representatives and the IMPRS board. The IMPRS board further suggested to apply this as an overall rule for all astronomy students in Heidelberg (if it is possible to realize for a funding budget).

Fig. IV.1.1: Participants of the 13th IMPRS-HD summer school, "Gaia Data & Science".



Credit: Christian Fendt, MPIA

Credit: Christian Fendt, MPIA

Fig. IV.1.2: Participants of the IMPRS-HD seminar retreat in Annweiler-Trifels.

The financial situation 2018 allowed the IMPRS-HD to grant Mattis Magg (ITA, supervisor Ralf Klessen) and Theodoros Soultanis (HITS, supervisor Friedrich Roepke) an IMPRS fellowship, as they were selected by the IMPRS board as the best applicants. Due to the recent student salary increase we expect to be able to offer only one fellowship per generation in the coming years.

Among the 271 applicants in 2018 (for PhD positions starting in 2019), 92 were female. This corresponds to 34 % and is similar to (if slightly higher than) the last years. More male applicants (59%) were rejected for the long shortlist than female applicants (50%). Interestingly, the percentage of female applicants who were ranked higher in the shortlist was higher (37%).

Applications arrived from all over the world, in particular many from India (61). Compared to recent years the number of Chinese applications was rather low (10) – similar in number to Chilean (7) or Iranian (14) applications. Rather many application arrived from the US (10), the UK (10), and also the Netherlands (14). Also, Italy was again another source of strong applicants (16). As always, the current location of the applicant and her / his citizenship is not always identical. For example, only 5 of the 14 applications arriving from the Netherlands were from Dutch nationals. Twenty-six IMPRS students completed their PhD in 2018. The MPIA students among them are listed in Table IV.1.1.

The 2018 IMPRS-HD summer school was on the topic of "Gaia Data & Science" – a timely choice, given the 2nd Gaia data release in April 2018. The scientific program was organized by Andreas Just and Stefan Jordan (both from the ARI). Invited lecturers were James Binney (Rudolf Peierls Centre for Theoretical Physics, Oxford), Angela Bragaglia (INAF-Observatory of Astrophysics and Space Science), Anthony Brown (Leiden Observatory), Laurent Eyer (Observatoire de Geneve), and François Mignard (Université Côte d'Azur). The international announcement was followed by about 60 applicants of which 53 were accepted as participants. About 80 % of the participants were from outside Heidelberg.

Christian Fendt

Table IV.1.3: PhDs completed by MPIA students in 2018.

Name	Defense Date	Title	Supervisor
Roxana Chira	21 January	On Filaments within Molecular Clouds and their Connection to Star Formation	Henning
Adriana Pohl	24 January	Structure of Planet-forming Disks: Multi-wavelength Polarization Diagnostics	Henning
Thales Gutcke	03 May	The quenching of star formation in galaxies	Macciò
Andreas Schreiber	18 May	Diffusion Limited Planetesimal Formation	Klahr
Jonas Frings	11 July	Structure and evolution of simulated dwarf galaxies and Milky Way satellites in Cold and Warm dark matter models	Macciò/ Schäfer (ARI)
Chiara Mazzucchelli	13 July	The Physical Properties and Cosmic Environments of Quasars in the First Gyr of the Universe	Walter
Tobias Buck	19 October	On the formation of the Milky Way system in cosmological context – A numerical study	Macciò
Michael Walther	28 October	Monitoring Thermal Evolution in the Intergalactic Medium over 12 Billion Years	Hennawi
Sara Rezaeikhoshbakhat	09 November	3D map of the dust distribution in the Milky Way	Bailer-Jones
Michael Rugel	21 November	On the formation and destruction of molecular clouds with the Galactic plane survey THOR	Beuther

IV.2 Academics, Education and Public Outreach

Public Outreach

Astronomy is a fascinating subject, and the astronomers at the Max Planck Institute for Astronomy have long seen it as part of their responsibilities to reach out to the general public, to teachers and pupils, and to the media. To that end, our researchers answer media enquiries as well as travel to locations throughout Germany (and sometimes beyond!) to talk to general audiences about their work. The science highlights in chapter II of this annual report were all published in the form of press releases, and led to widespread coverage of MPIA research results.

For the Max Planck Society as a whole, 2018 was a special year, with the society's 70th anniversary, the 100th anniversary of the Nobel prize for Max Planck, and Max Planck's 160th birthday combined. To celebrate, the MPG launched a social media campaign with hashtag #wonachsuchstdu, "What are you looking for?", highlighting human curiosity as the drive for fundamental research. The campaign involved German YouTubers MrWissen2Go and Doktor Whatson travelling throughout Germany and visiting selected Max Planck Institutes, and culminated in the "Max Planck Day" on September 14, 2018. MPIA, in collaboration with the other three Heidelberg Max Planck Institutes, expanded this into a "Max Planck Week", held at DAI (the "German-American Institute") in central Heidelberg, which was also billed as a warm-up for the International Science Festival "Geist Heidelberg" (organized by MPIA's scientific coordinator Klaus Jäger and his counterparts in the other three institutes). Max Planck Week featured four talks, one from each institute, with MPIA director Hans-Walter Rix taking visitors on a tour of "Our Galaxy in Five Dimensions". On Max Planck Day itself, the week culminated in a panel discussion that included MPIA director Thomas Henning, and addressed the "Big Questions and Breakthroughs in Science", including the interactions of science and society. The evening was rounded off by a Science Slam, organized by students including MPIA's Aida Ahmadi and Asmita Bhandare, which saw MPIA PhD student Néstor Espinoza slamming about "Exoplanets: A Search for New Worlds". Combined, the Max Planck Week events reached an audience of 1500 visitors. Throughout the week, selected exhibits from the joint exhibition "Astronomy For Everybody" of MPIA and Haus der Astronomie were on display in the DAI Library (organized by Markus Nielbock).

As in the past years, numerous education and outreach activities were carried out at Haus der Astronomie (HdA), our center for astronomy education and outreach on our Königstuhl campus, operated by the Max Planck Society and administered by MPIA. A detailed description of these activities can be found in section IV.3. In particular, MPIA scientists make up a significant number of speakers for the public talk series on Königstuhl.

For members of the general public, guided tours of the Königstuhl Campus offer a chance to experience a research environment at first hand. The tour guides are the MPIA Outreach Fellows: PhD students at the insti-

Fig. IV.2.1: Panel discussion on Max Planck Day, September 14, 2018. *Left to right:* Prof. Dr. Kai Johnsson (Max Planck Institute for Medical Reseach), Prof. Dr. Anne Peters (Max Planck Institute for Comparative Public Law and International Law), moderator Jakob J. Köllhofer (Director of Deutsch-Amerikanisches Institut), Prof. Dr. Klaus Blaum (Max Planck Institute for Nuclear Physics), and Prof. Dr. Thomas Henning (Max Planck Institute for Astronomy).

Credit: Markus Nielbock, MPIA

Fig. IV.2.2: Participants of the joint MPIA / HdA Girls' Day 2018.

Fig. IV.2.3: The MPIA graphics department created flags for the Max Planck Week for all Heidelberg Max Planck Institutes. The flags were flying for one week over the Theodor-Heuss-Brücke, Bismarckplatz and at the train station.

tutes who spend part of their time gaining experiences in public outreach. These guided tours typically include a visit to MPIA's 70 cm KING telescope and to the magnificent scale model of the Sun's 100 nearest stellar neighbours, created by MPIA's technical departments. The guided tours are offered in cooperation with the neigbouring Landessternwarte.

MPIA also has offers aimed directly at high school students. One is the High School Internship program (organized by Klaus Meisenheimer), aimed at pupils in 10th and 11th grade. In coorperation with the Landessternwarte and Astronomisches Rechen-Institut (both part of Heidelberg University's Center for Astronomy, ZAH), we have been offering this kind of internship program since 2002. This year's internship program, on October 9–13, introduced 10 pupils to basic concepts as well as to practical methods of astronomy.

In addition, in cooperation with HdA, the MPIA is a regular participant in the nation-wide Girls' Day: a one-day program aimed at female pupils aged between the ages of 13 and 18 (Renate Hubele, Sigrid Brümmer and MPIA PhD student Melanie Kaasinen). The purpose of Girls' Day is to provide female pupils with the opportunity of experiencing professions in which women are underrepresented. For this year's Girls' Day on April 26, a total of 16 young women were able to use telescopes from the Las Cumbres Observatory's global network, controlled remotely via the Internet, to observe star clusters and nebulae. The Girls' Day was organized in collaboration with the SFB 881 Collaborative Research Center "The Milky Way System".

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

IV.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 MPIA Campus. Its mission: to communicate the fascination of astronomy to the general public, to support astronomy education, and to foster the exchange of knowledge between scientists.

Haus der Astronomie is an unusual institution at the interface between science and the public. Its custom-built, galaxy-shaped building hosts an active team of astronomers and astronomy educators dedicated to developing and producing materials and resources for the public or for use in schools. In 2018, the HdA building received more than 11,000 visitors: members of the general public coming for guided tours or popular talks, student groups from kindergarten to university level, educators and teachers participating in workshops or lectures, and scientists and engineers attending meetings or conferences.

Astronomy for the general public

Our outreach activities for the general public combine the tools of classic public relations, online outreach and the organization of public events. As the German node of the ESO Science Outreach Network (ESON), we provide support for the German-language outreach activities of ESO, the European Southern Observatory (M. Pössel, C. Liefke, M. Nielbock).

On-site events for the public included our monthly series of talks "Fascinating Astronomy", with a total of 13 events (C. Liefke) and "Sunday a.m. Astronomy" with five events on the occasion of the 120th anniversary of the neighbouring Landessternwarte Königstuhl (which is part of the Zentrum für Astronomie der Universität Heidelberg, one of HdA's partner institutions). Our program also featured two family events at Christmas time (N. Fischer, E. Kolar). The "Science Meets Fiction" format of combining short scientific talks with the presentation of a science fiction movie continued this year with the films "Deep Impact" (on the occasion of the international "Asteroid Day"), "2001 – Odyssee im Weltraum (A Space Odyssey)" and "Aufbruch zum Mond (First Man)" (the latter not at HdA, but at Gloria cinema in Heidelberg's old town), introduced by C. Liefke and M. Nielbock.

Former ESA astronaut Dr. Thomas Reiter, who spent over 350 hours in space on the MIR and ISS space stations, visited Haus der Astronomie on December 11th to give a sold-out public highlight lecture on "Current developments and the future of manned and robotic spaceflight in Europe" (M. Nielbock).

Our auditorium was filled with the sound of classical music in "Musikalische Sternstunde", thanks to Trio Stardust Sinfonie Music ensemble, whose performance was combined with a planetarium show (N. Fischer, T. Müller). Much more modern sounds could be heard in our auditorium at "Sternbild: Mensch I", the first of a six-part concert series by KlangForum Heidelberg. Under the direction of Walter Nußbaum, the Schola Heidelberg and the ensemble aisthesis performed world premieres

Fig. IV.3.1: The HdA building in February 2018.

Credit: Markus Pössel, HdA

Credit: Markus Pössel, HdA

Fig. IV.3.2: "Sternbild: Mensch I" by KlangForum Heidelberg in the HdA auditorium on November 16, 2018.

for works by Matthias Ockert and by Bernhard Lang, complemented by works by Schütz, Sciarrino, Maderna, Stockhausen, and des Préz. The musical performance was complemented by texts and planetarium elements presented by M. Pössel (Fig. IV.3.2).

As of 2018, HdA and MPIA are partners of the Heidelberg branch of the European Researchers' Night. This EU project, led by EMBL, lasts for 18 months. In this framework, HdA / MPIA organized a public event on September 28th with various activities for the general public which attracted 400 visitors (M. Nielbock et al.), including a concert featuring a live performance of Gustav Holst's "The Planets" complemented by a fulldome planetarium show and narration (N. Fischer, T. Müller). Combined, these on-site events drew an audience of almost 2700 visitors.

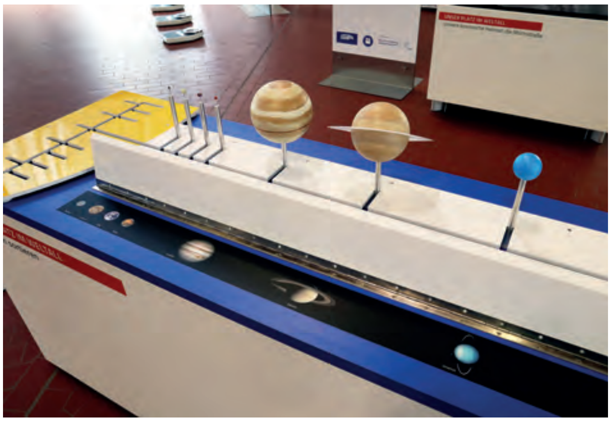
For particularly interested members of the public and in particular for students at the University of Heidelberg, M. Pössel (with H. Klahr) offered a lecture series "Astronomie für Nichtphysiker: Das Sonnensystem und seine entfernten Verwandten" ("Astronomy for Non-Physicists: The Solar System and its distant relatives") as an introduction to the methods of astronomy for non-physicists. Additionally, we offered a one-day workshop on astrophotography for the general public (C. Liefke, M. Penselin).

On the occasion of the total lunar eclipse on July 27th, the Haus der Astronomie invited to a public observation in the city of Heidelberg. Equipped with three telescopes, the course of the eclipse as well as some bright planets were observed together with several thousand visitors, who were attracted by an extensive coverage in the media (M. Nielbock, C. Liefke).

On October 14th, HdA participated in a Space Awareness Day of the Technikmuseum Speyer, which celebrated the 10th anniversary of its space exhibition (M. Nielbock, C. Liefke, M. Pössel). HdA staff also gave around 20 public talks in various locations throughout Germany.

Explore Science and Astronomie für Alle

As in previous years, the largest external science event we participated in was "Explore Science" on June 13 – 17, the Klaus Tschira Foundation's five-day family science festival, attended by 52,000 visitors. But this time was special: This year's theme was astronomy, and Haus der Astronomie, together with the Max Planck Institute for Astronomy, was in charge of creating Explore Science's central exhibition, funded by the Klaus Tschira Foundation. The exhibition is titled "Astronomy für Alle", literally "Astronomy for everybody", and consists of twenty interactive exhibits, with the overarching themes "Eyes to the Sky", "Our Place in Space", "Stars: Distant Suns", and "Alien Worlds". The exhibits themselves include a demonstration experiment for the parallax effect, a real meteorite that visitors can pick up, an exoplanet wheel of fortune allowing visitors to experience the rarity of habitable exoplanets, and a giant planisphere (Fig. IV.3.3). Also, there are three touch-tables programmed by HdA's T. Müller, which provide for a hydrogen fusion game, a Solar System gravity simulator in which visitors build their own planetary system and can trace its evolution by running an N-body simulation (Fig. IV.3.4), as well as an interactive guide to the Milky Way galaxy, respectively (which was created in partnership with the collaborative research center SFB 881). Most of the exhibition, as well as our activities for younger children (organized by N. Fischer) were also a part of the "Explore Science" in Bremen, from August 30 to September 1, the first such event in Bremen. At the time of this writing (in Summer 2019), the exhibition is on display on the island of Mainau in Lake Constance.



Credit: Markus Pössel, HdA

Fig. IV.3.3: Part of our "Astronomie für Alle" exhibition: Put the planets into their proper order.

Scientific exchange

Haus der Astronomie is regularly used as a venue for scientific conferences, with the central auditorium and the workshop rooms suitable for hosting meetings with up to 90 participants. The 2018 MPIA Summer Conference "Stellar halos across the cosmos" brought more than 80 scientists to HdA from July 2 – 6. Additional conferences this year were the Heidelberg-Harvard Workshop "Physics of Star Formation: Gas flows from Milky Way cloud scales to protostellar disks" in December and "Survival of Dense Star Clusters in the Milky Way System" in November, both organised in collaboration with the Collaborative Research Center SFB 881 "The Milky Way System", of which HdA is the outreach partner. In addition, 39 smaller scientific and organizational meetings took place in HdA. All in all, more than 1500 scientists and engineers used the HdA as a place for meetings, discussions, and presentations.

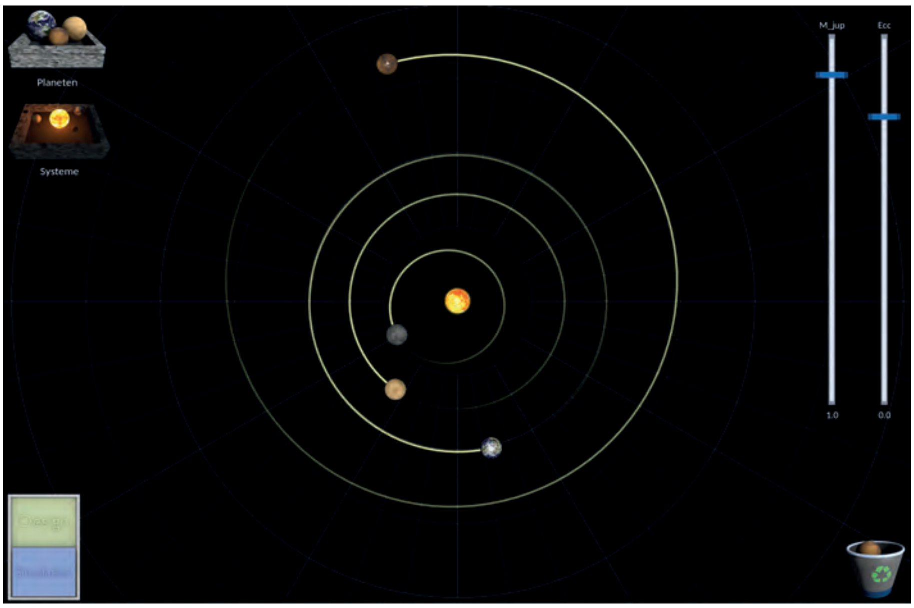
Visualization

Led by our visualisation specialist T. Müller, HdA's has undertaken significant activities in this area – part of our concept from the beginning, but feasible only now that we have a resident expert. Müller's work shows, in an exemplary manner, HdA's role as a bridge between the research community and the public, with projects ranging from visualizations that directly aid the scientists in their research to those which help present their results to a general audience. Formats range from standard movies for presentations to fulldome content, suitable for display in a planetarium.

Regarding public-facing visualisation, in cooperation with the MPIA's Planet and Star Formation theory group (H. Klahr) and the University of Kiel's astrophysics group (S. Wolf), Müller produced a five-minute fulldome movie, which showcases a circumplanetary disk simulation. The movie was submitted to the 12th Fulldome Festival in Jena, and received a citation as a 2018 Fulldome Festival Finalist (Fig. IV.3.5). Visualisation support for HdA events, notably Researchers' night and our exhibition "Astronomie für alle" also proved essential.

On the research side, Müller continued a number of successful collaborations with Heidelberg astronomers. This included a student internship (H. Schwanekamp) in cooperation with MPIA's PSF theory group (H. Klahr) about line integral convolution rendering for 3D vector fields (Fig. IV.3.6), and a cooperation with Astronomisches Recheninstitut (T. Sagrista) and the Visual Computing Group (F. Sadlo) at the University of Heidelberg resulted in a paper ("Gaia Sky: Navigating the Gaia cata-

Fig. IV.3.4: Touch table application as part of our "Astronomie für Alle" exhibition, which allows visitors to design customized planetary systems and follow their evolution in time.



Credit: Thomas Müller, HdA

Credit: Thomas Müller, HdA

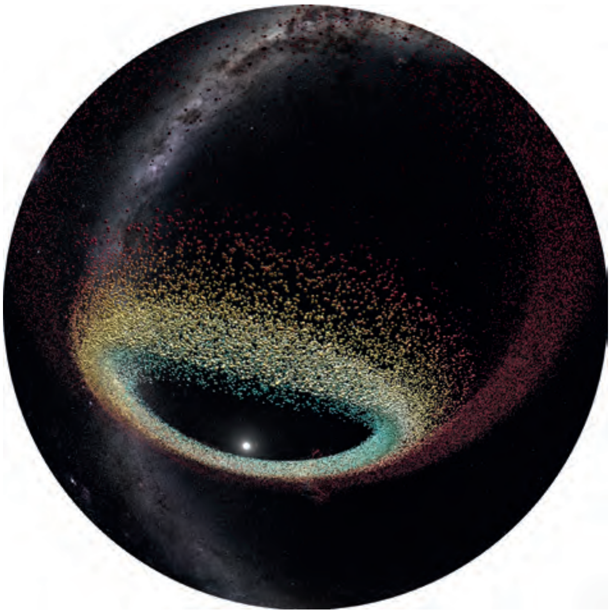
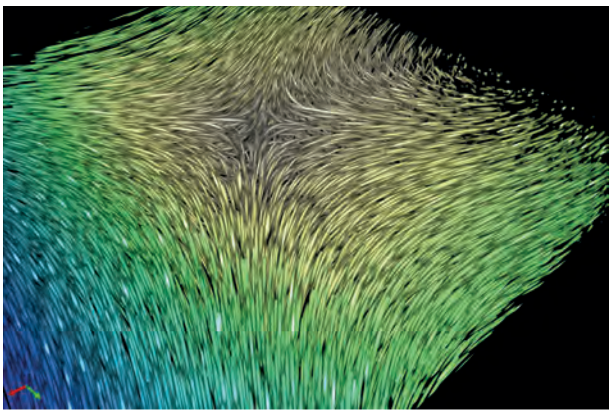


Fig. IV.3.5: Fulldome Festival Finalist: Still frame from the fulldome visualization of a circumplanetary disk simulation using tracer particles to highlight the underlying vector field (In collaboration with H. Klahr, MPIA Heidelberg, and S. Wolf, University of Kiel).

log") presented at the IEEE Vis conference in Berlin. In 2018, Müller also has started the implementation of the standalone software Thalia for 2D- and 3D-visualizations of datasets in the context of the THOR project (PI: MPIA's H. Beuther).

As for the associated dissemination activities, in 2018 HdA and the planetaria Mannheim and Kassel held two workshops for planetarium practitioners and scientists, on the topic of the fulldome astronomy software Uniview. To ease the handling of a number of Uniview functions, Müller developed an associated Java application. At the final colloquium of the Collaborative Research Center 716 (Uni Stuttgart), Müller gave a fulldome presentation about "Visualization at the HdA".

Fig. IV.3.6: Visualizations for science: 3D Line-Integral-Convolution visualization of an artificial vector field.



Credit: Hendrik Schwanekamp, HdA

Astronomy for schools and kindergartens

Our flagship education project remains "Wissenschaft in die Schulen!" (literally "Science into the schools!", abbreviated WIS) in cooperation with the popular astronomy magazine Sterne und Weltraum, which is part of the Spektrum der Wissenschaft / SpringerNature family of magazines. WIS astronomy is led by HdA senior staff member O. Fischer who, with his team of (mostly external) authors created 13 sets of curricular materials helping teachers bring cutting-edge astronomy into their classrooms, kindly supported by the Reiff Foundation for Amateur and School Astronomy.

Our most successful product continues to be "Universe in a Box", an astronomy kit for use with kindergarten or elementary school children (developed by former MPIA staff member Cecilia Scorza with contributions from N. Fischer). The kit is in use in more than 70 countries. Interested schools and kindergartens can directly borrow Universe in a Box kits from Haus der Astronomie. Selected "Milky Way" kit materials, developed as part of the Collaborative Research Center SFB 881 "The Milky Way System", for which HdA is the key outreach partner, were extended and adapted for younger students. SFB 881-related workshops were offered as well. Our outreach work for SFB 881, pioneered by Cecilia Scorza (now at LMU Munich) and expanded by R. Hubele, was highlighted by Deutsche Forschungsgemeinschaft on their website, and featured as a best-practice example at DFG's presentation at the 11th Forum Wissenschaftskommunikation in Bonn.

Since March 2015, HdA has been a partner in the EU-funded Horizon 2020 project EU space awareness, developing educational resources related to the ESA programmes Galileo and Copernicus as part of that collaboration. By the end of the project in early 2018, we had produced 44 new activities and resources: 15 on the subject of climate change, to be collected in a "Climate Box", 5 dealing with navigation, and 24 on the topic of history of astronomy alongside with a toolbox with hands-on materials (C. Scorza, M. Nielbock).

In May 2018, HdA initiated a new collaboration with DLR (German Aerospace Center) and the Joachim Herz Foundation to develop teaching materials connected to the second mission of German ESA astronaut Alexander Gerst to the International Space Station, called "Raum für Bildung" (literally "Space for education"; M. Nielbock, M. Pössel). In June 2018, a scale model of the Solar System, developed and built by primary school children in cooperation with the HdA was inaugurated in a public forest area (N. Fischer).

On June 30, 2018, former NASA Space Shuttle astronaut Wendy Lawrence and former NASA engineer Cathy Watson visited HdA and MPIA. During a meeting with MPIA students and postdocs, they talked about their careers and work, and with the young children of an astronomy workshop in HdA, they talked about the benefits and challenges of human spaceflight (M. Nielbock, N. Fischer, M. Pössel).

Over the course of the year, more than 3000 pupils and pre-school children visited HdA for a total of 169 workshops for various age groups. Such workshops typically involve hands-on activities, make use of our digital planetarium, and are often used to field-test newly developed materials. Our workshops and associated development activities are ably supported by three teachers, seconded by the Baden-Württemberg Education Ministry, who spend one day per week at HdA, the other days in their schools: Matthias Penselin (Albert-Schweitzer-Gymnasium, Crailsheim), Florian Seitz (Hebel-Gymnasium, Schwetzingen) and Martin Wetz (Internationale Gesamtschule Heidelberg). This year, we again developed new workshop concepts in cooperation with Junge Uni Heidelberg (N. Fischer) and for this year's Explore Science (N. Fischer), both centered on constellations and how to find them. For the Researchers Night a turnable star chart was developed (T. Müller, R. Hubele, N. Fischer) and printed 5000 times. In addition 30 Space Scoops, astronomical news aimed at elementary school-age children, were translated into German and put online on the Space Scoop Online platform (N. Fischer, M. Nielbock, R. Hubele, M. Jäger).

External events for pupils included a course with the aim to program a star map as part of the Deutsche Schülerakademie (O. Fischer), a five-day course for students at the Bildungscampus Heilbronn on the topics of navigation, remote sensing and celestial mechanics (O. Fischer, M. Nielbock), two contributions to the Children's University of the Academia Engiadina in Samedan, Switzerland, for primary school children (M. Nielbock), and a two-day workshop about visualization in the context of special relativity for 20 students of the Goethe Gymnasium Weißenfels (T. Müller). C. Liefke accompanied the AGN monitoring team of the Naturwissenschaftliches Labor des Friedrich-Koenig-Gymnasium in Würzburg during their field trip to the Roque de los Muchachos Observatory on La Palma, and M. Nielbock served as a jury member of the FIRST Lego League regional elimination contest in Heidelberg.

Reaching out to communicators and educators

Teachers and educators play a key role in science outreach. Helping them develop a passion for cutting-edge research, and giving them proper tools to pass this passion (and the science itself!) on to their students, is probably the most effective outreach strategy there is.

Pre-service training included two seminars (O. Fischer, C. Liefke) and the annual block course "PASTRO: Introduction to Astronomy for pre-service teachers" (O. Fischer, C. Liefke, M. Pössel, M. Nielbock) at the University of Heidelberg, as well as a lecture on "Basic Astronomy in School" at Heidelberg's University of Education (Pädagogische Hochschule, N. Fischer). For the PASTRO course, we laid the first foundations for putting the course on an "inverted classroom" footing, where for each topic, students prepare beforehand using custom-made videos and lecture notes, whereas classroom time is used for interactive learning (such as solving problems and experimenting). We secured a grant from the Carl Zeiss Foundation for implementing this structure over the following two years.

During this year, eight students aiming to become physics teachers were working on their masters thesis (in its German incarnation as "Staatsexamensarbeit") or bachelors thesis at HdA, with topics ranging from solar observation, orrery programming, conception and construction of an all sky camera and a weather station, measuring the effect of refraction, using Gaia-data for Hertzsprung-Russell diagrams to cosmic extinction and the Olbers paradox.

In-service training at Haus der Astronomie included our nationwide three-day training course "Hitchhiker's Guide to the (Milky Way) Galaxy" in November, funded by the Wilhelm und Else Heraeus foundation (Fig. IV.3.7; O. Fischer), and the one-day course "The Digital Universe – Computers in Astronomy Educa-

Credit: Olaf Fischer, HdA

Fig. IV.3.7: Group photograph for our nationwide teacher training event in November.

Fig. IV.3.7: Three Chilean teachers visiting HdA for in-depth in-service training in astronomy education.

tion" for the Baden-Württemberg education ministry (M. Pössel). For primary school and kindergarten teachers, there were 22 training sessions, six workshop sessions and numerous consultations (N. Fischer). The HdA participated in two conferences in the area of kindergarten and primary school with lectures, workshops and booths (N. Fischer).

External teacher trainings took place in Thuringia (2 days at Sonneberg observatory, O. Fischer) and in Baden-Württemberg (3 days in the state academy for continued professional education Bad Wildbad, as part of a three-year cycle; O. Fischer, M. Penselin), while this year's mobile teacher training (O. Fischer), supported by the Reiff Foundation, took place in Saxony-Anhalt (Dessau, Merseburg), Thuringia (Gera), the Rhineland (Ludwigshafen, Ingelheim, Simmern / Hunsrück) and Saarland (St. Ingbert). This year's edition of "Astronomy from Four Perspectives", our German-Italian summer school funded by the WE Heraeus Foundation, took place in Padova.

Our "Telescope Driver's License" workshop, well-established by now, which qualifies teachers for the use of small telescopes in school took place at the "Rhöniversum" Umweltbildungsstätte Oberelsbach and at HdA (C. Liefke). The course also qualifies teachers for HdA's telescope lending program, which expanded, funded by the Reiff-Stiftung für Amateur- und Schulastronomie, to a total number of 36 telescopes (12 Dobsonians and 24 refractors on equatorial GoTo mounts; C. Liefke). HdA staff also contributed to a 5-day teacher training course of the German Physical Society on astro- and geophysics in Bad Honnef (C. Liefke, M. Penselin) and a one-day course on astronomy at the Pädagogisches Landesinstitut Rheinland-Pfalz in Speyer (R. Hubele, C. Liefke, M. Penselin).

Astronomy education and outreach is crucially dependent on the conditions for teaching astronomy in schools and on a pool of teachers capable, and enthusiastic about, teaching astronomy. HdA is involved in creating astronomy-friendly conditions on several levels. The University of Heidelberg, one of the HdA partners, is in the process of reforming their physics teacher curriculum; we are supporting them in the creation of an astronomy minor for the master of education degree ("Erweiterungsfach Astronomie im Master of Education"). HdA has actively supported this process, and expanded its role in teacher training at the University of Heidelberg. In Baden-Württemberg, the German state that includes the city of Heidelberg, we supported the education ministry in establishing the new subject "Computer Science, Mathematics, Physics" (IMP) over the past years; this year, M. Pössel was involved as an advisor to the Landesinstitut für Schulentwicklung for the state's new astronomy and astrophysics curriculum.

Research with high school students

HdA provides first-hand research experience for high school students in several different programs. In the framework of the IASC-Pan-STARRS asteroid search campaigns, high school students search for asteroids in Pan-STARRS image data, with a realistic chance of discovering previously unknown main belt asteroids. Within this framework, we supported a total of 40 German high school groups participating in four search campaigns (C. Liefke).

With the common scheduling system still in place, a new interface that allowed to re-establish real-time remote observations with the Faulkes / LCOGT telescopes was introduced and extensively tested beforehand, with selected partners, including some of the HdA partner

Fig. IV.3.8: Haus der Astronomie Event Posters, created by the MPIA graphics department.

Credit: MPIA graphics department

schools (C. Liefke). The Faulkes / LCOGT telescopes also played a major role in an asteroid search project supported by C. Liefke and conducted at the Paul-Pfinzig-Gymnasium in Münster, which won the state-wide Nordrhein-Westfalen science competition Schüler Experimentieren. Subsequently, the project was continued as a recovery program within the Jugend Forscht competition.

Due to major technical issues, usage of the ROTAT remote observatory proved to be difficult for less experienced observers in 2018. The telescope has nevertheless been used frequenly for near-earth and minor planet discoveries (C. Liefke). The project on exoplanet transits started in 2017 and supervised by C. Liefke entered the state-wide Jugend Forscht Baden-Württemberg science competition.

Within the framework of their Hector Seminar cooperation phase project, two students developed a procedure to determine the position of the dome slit of HdA / MPIA's 50 cm telescope with a photoelectric sensor, which is an important part of the efforts to enable remote observations of the telescope (C. Liefke, M Pössel). By the end of the year, a new project dedicated to track the passage of comet 46P/Wirtanen started with two new students. High school students at the Astrophysik-AG of Heidelberger Life Science Lab worked on a self-constructed Cherenkov telescope, strategies to discover the elusive Planet Nine and astrophotography.

Our internship program in 2018 included three separate "BOGY" career orientation weeks, with a total of 18 participants, one of them allowing for a two-week extension (C. Liefke und T. Müller). One of the internship weeks was about using visualization for education", using astronomical star catalogues and scalar data visualization of a supernova dataset.

Our three-week International Summer Internship, which we offered twice this year and which regularly includes participants from the International Summer Science School Heidelberg, saw a variety of student research projects making use of online catalogues and images (M. Pössel), with 15 participants from Germany, USA, Australia, Bangladesh, Great Britain, France, Egypt and Slovakia. Furthermore, we had five interns staying between two and ten weeks throughout the year. Research subjects for the interns ranged from Solar spectroscopy to an inquiry of stellar ages with the help of Gaia DR2 data and the MESA stellar evolution simulation software as well as to tracing the orbit of the star S2 around our Milky Way's central black hole using ESO archive data from the NACO instrument.

Networking

Internationally, our main collaborations are in the framework of the UNAWE and EU Space Awareness networks, as well as part of the DAAD Center of Excellence in Investigation and Teaching (Astronomy) of the Heidelberg University. Regionally, we continued our fruitful collaboration with Forscherstation, the Klaus Tschira Center for Early Science Education in Heidelberg. The collaboration includes a joint appointment (N. Fischer) for the development of educational materials and teacher workshops.

HdA also maintains a network of partner schools throughout Germany, encompassing 41 schools in 15 of Germany's 16 federal states. The network was originally established for secondary schools; this year, the first primary school joined the partner school network. Of course, we also collaborate with a number of additional national and international institutions. For instance, there is a fruitful collaboration with Chile, which has resulted in teacher training events reaching (so far) nearly 1000 teachers throughout the country since 2010, from Arica in the North to Puerto Montt in the South, and also in 15 German teachers getting the opportunity to visit the Chilean observatories as well as in Chilean teachers visiting HdA for in-depth training (Fig. IV.3.8). With the Clube de Astronomia Louis Cruls, a new collaboration has been established with Brazilian educators (C. Liefke).

Our collaboration with ESO on the "ESO Supernova" (ES), a younger (and larger) sibling of HdA that opened in April 2018 in Garching near Munich, continued as well. Our contributions to the building's permanent exhibition are now open to the public; the workshops we helped the ES to develop and adapt are among those now offered to school classes by ES's education specialist (and former HdA partner teacher) Wolfgang Vieser, and additional avenues of collaboration are actively being explored.

Markus Pössel, Sigrid Brümmer, Natalie Fischer, Olaf Fischer, Renate Hubele, Esther Kolar, Carolin Liefke, Thomas Müller, Markus Nielbock, Matthias Penselin, Florian Seitz, Martin Wetz, and Jakob Staude

Dossenheim
Handschuhsheim
Wieblingen
Neuenheim
Ruprecht-Karls-Universität Heidelberg
Ziegelhausen
Schlierbach -Ziegelhausen
Heidelberg
Central Station
Bahnstadt
Eppelheim
Pfaffengrund
Südstadt
Königstuhl
Speyrerhof
MPI für Kernphysik
MPI für Astronomie
Bierhelderhof
Kohlhof
Pleikartsförsterhof
Kirchheim
Rohrbach
Patrick-Henry-Siedlung
Boxberg
Kirchheimer Hof
Emmertsgrund
Gaiberg
Bruchhausen
Lingental
Leimen
Sandhausen
St. Ilgen
Ochsenbach
Neckar
Mannheimer Straße
Dossenheimer Landstraße
Berta-Benz-Straße
Steubenstraße
Berliner Straße
Uferstraße
Neuenheimer Landstraße
Ziegelhäuser Landstraße
In der Neckarhelle
Schlierbacher Landstraße
Burgenstraße
Am Hackteufel
Schumannstraße
Vangerowstraße
Kurpfalzring
Henkel-Teroson-Straße
Eppelheimer Straße
Czernyring
Kurfürsten-Anlage
Rohrbacher Straße
Ringstraße
Speyerer Straße
Römerstraße
Bertha-Benz-Straße
Chaisenweg
Kohlhofweg
Drei-Eichen-Weg
Gaiberger Weg
A5
E 35
A656
B 3
B 37
B 535
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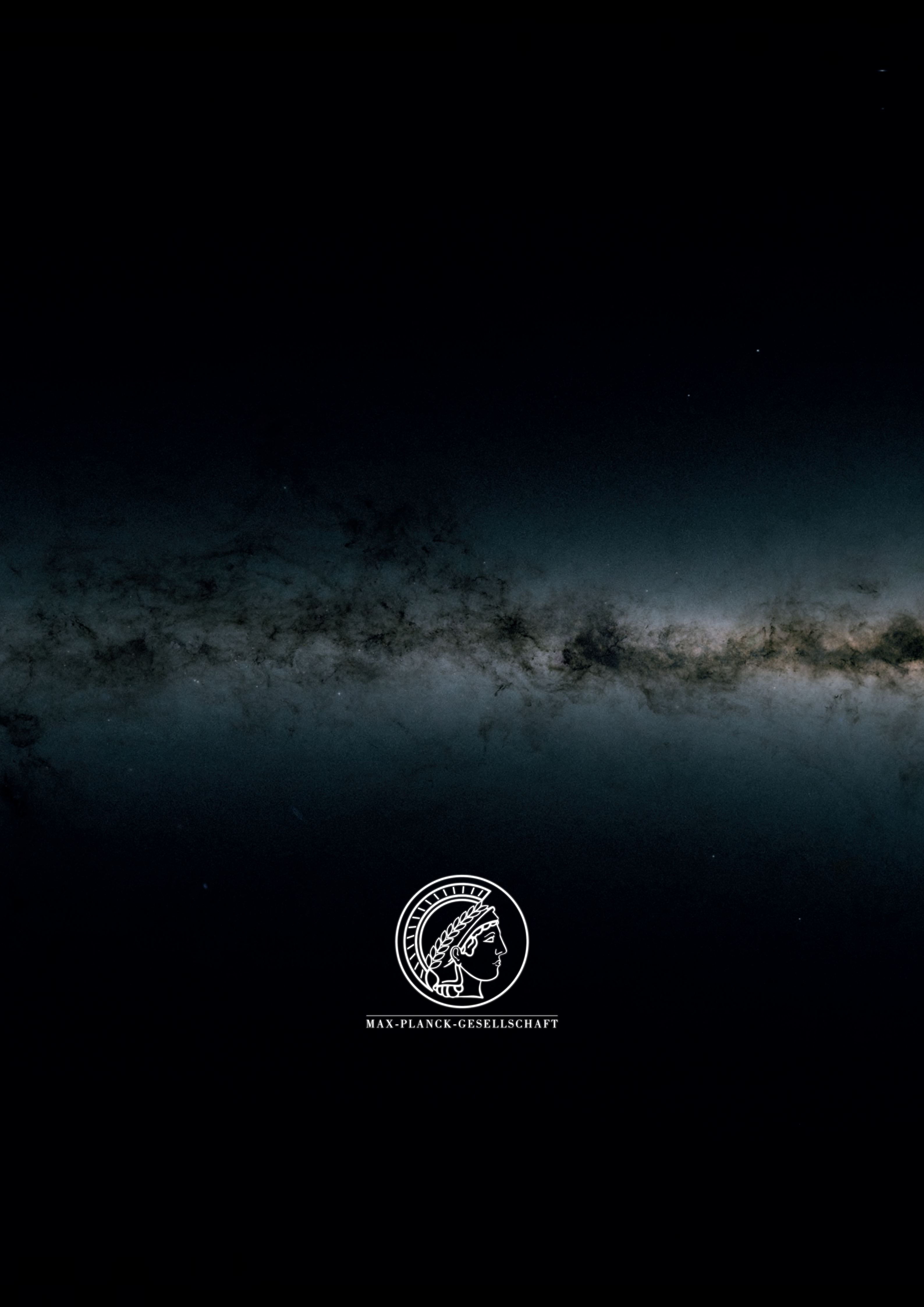

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