Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report 2019

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Max Planck Institute for Astronomy

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Prof. Dr. Thomas Henning (Director)

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Credit: M. Pössel / HdA

Preface

Our universe never ceases to amaze the human mind. It harbors an astonishing range of phenomena and physical conditions, it reveals an astounding level of self-organization and it 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 how galaxies, stars and planets form.

But as in all areas of research, progress in 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 in 2019, a historical year for us in two respects: With a large group of alumni, friends and current members, we had the opportunity to celebrate the 50th anniversary of our institute. In addition, our decade-long effort to strengthen the field of exoplanet physics at the institute and in the Max Planck Society as a whole finally came to fruition, with the approval of a new department on the Atmosphere Physics of Exoplanets at MPIA, to be led by Laura Kreidberg.

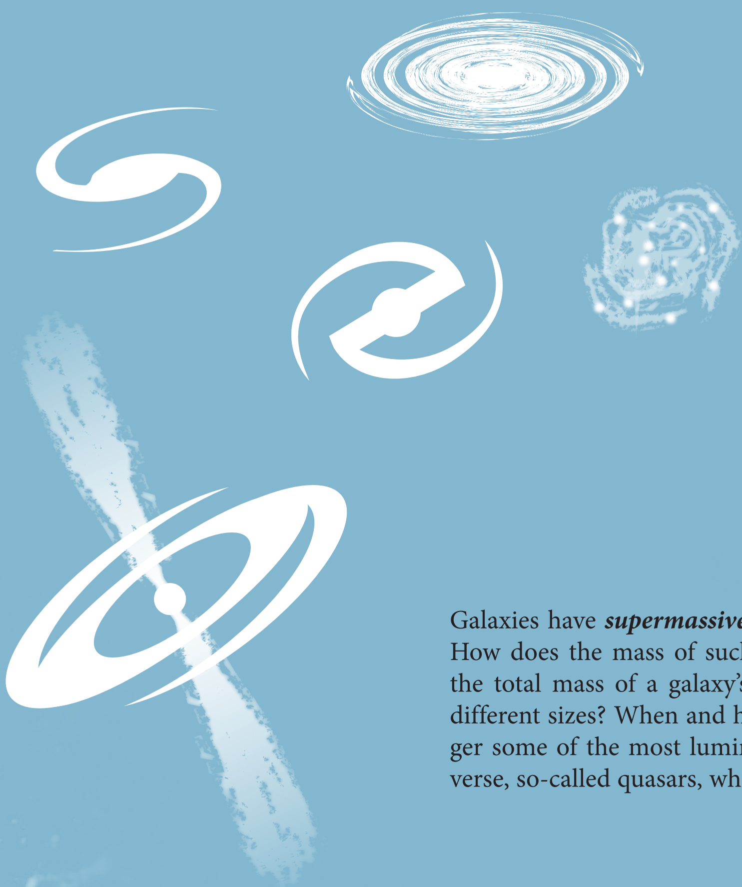
Hans-Walter Rix , Thomas Henning

Heidelberg, Oktober 2021

I. MPIA in a Nutshell

Credit: M. Pössel / HdA

Our Fields of Research: Galaxies and Cosmology

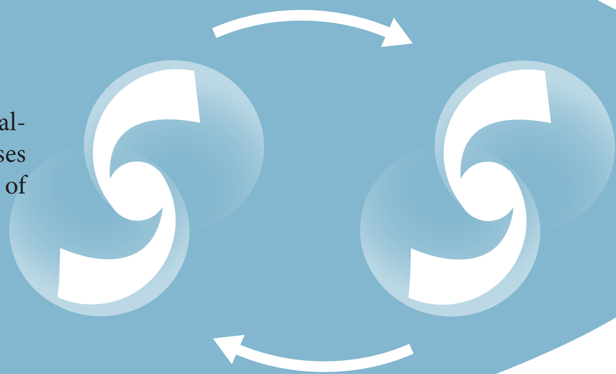


Galaxies come in many shapes and sizes. How do these differences arise? And what factors are responsible for how many stars a galaxy produces?

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

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

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

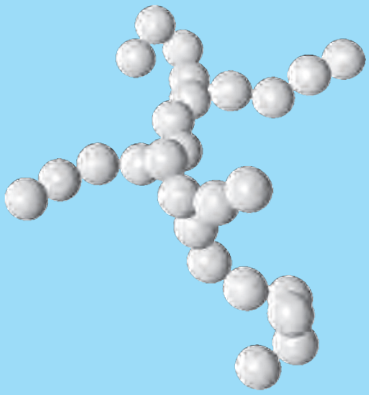


How are ***dark matter*** and hydrogen gas distributed on the largest ***cosmic scales***, across hundreds of millions of light-years? How is this distribution linked to the evolution of galaxies over billions of years? How did the complex structure of our Universe arise from an almost perfectly smooth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

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?



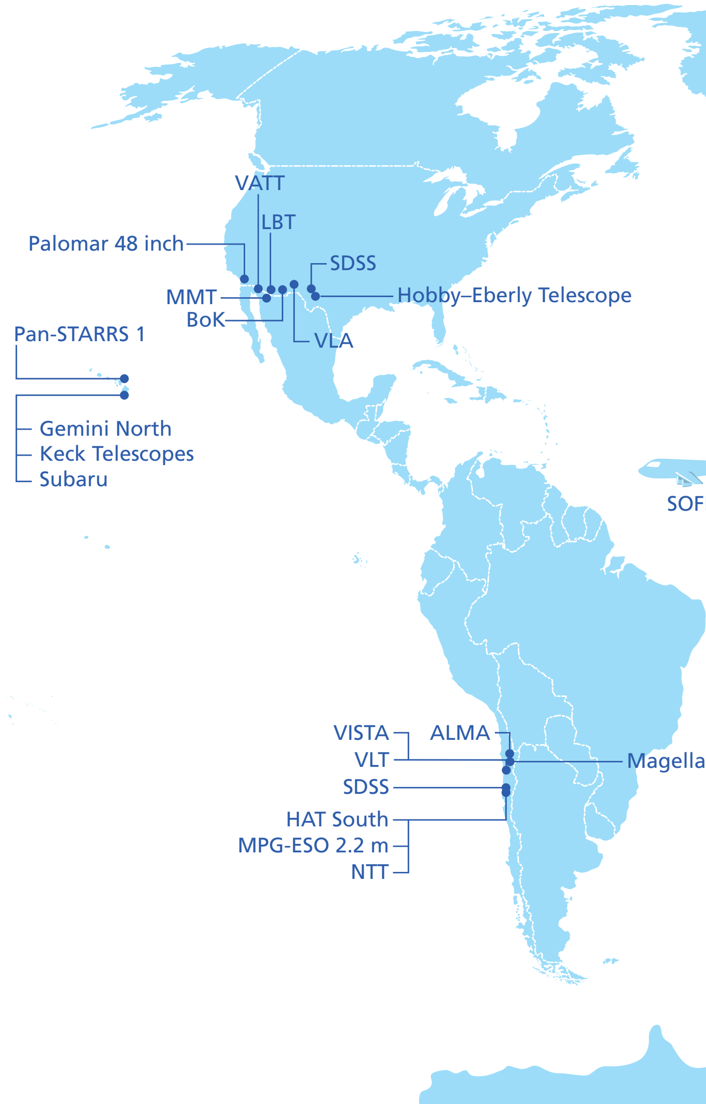
What are the ***stages of planet formation*** – from the first colliding ***grains of dust*** to objects thousands of kilometers across? What can laboratory experiments tell us about the properties of cosmic dust – and ways to detect these properties?

Since 1995, astronomers have discovered more than 4800 ***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 has contributed to several instruments for ESO's Very Large Telescope (VLT), and its astronomers frequently use the VLT for their research.

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



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

Credit: ESO / C. Malin

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

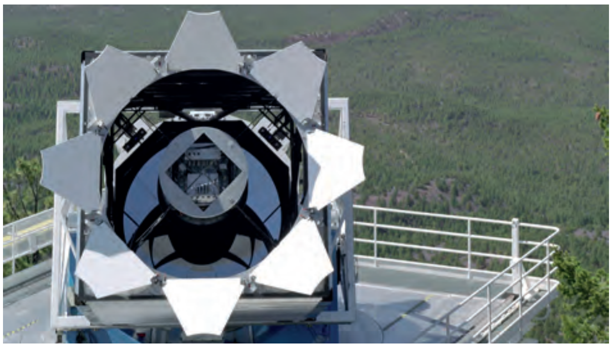
Credit: M. Pössel / HdA

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

Credit: NASA / J. Ross

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

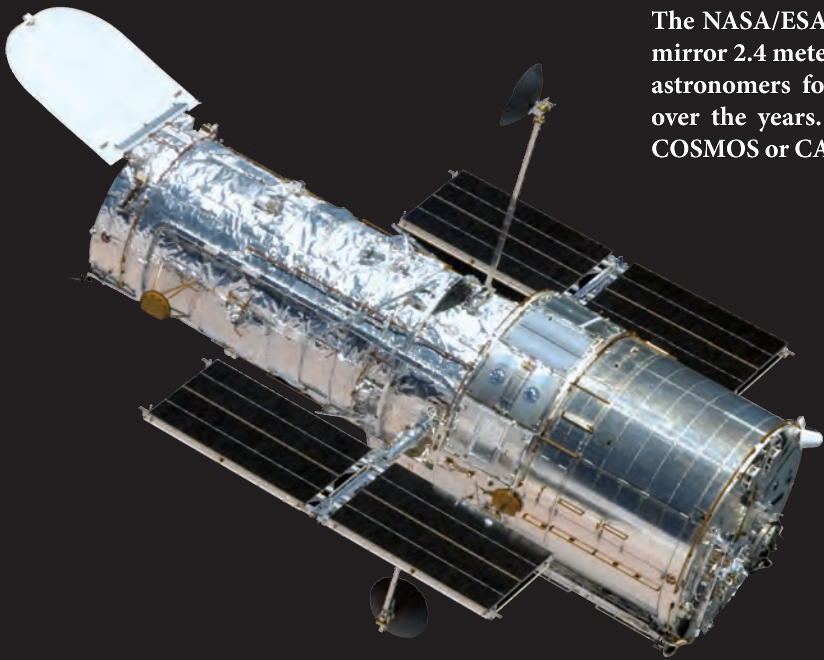
Credit: B. Tubbs



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

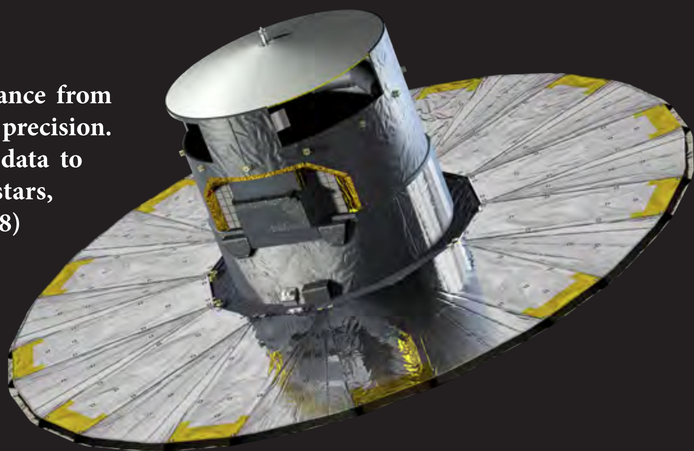
Credit: SDSS

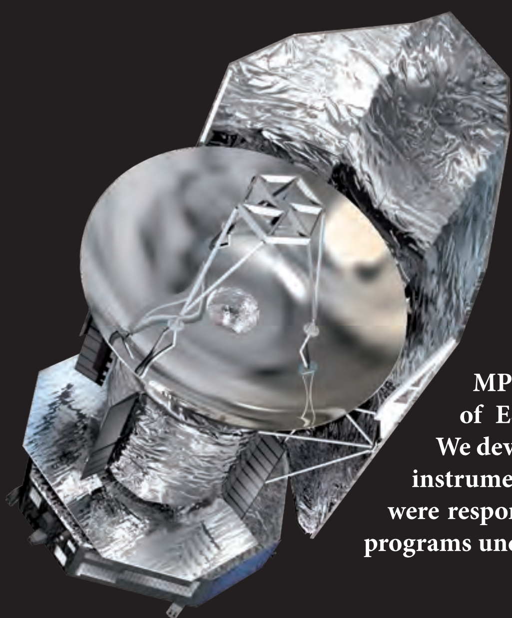
Space Telescopes



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

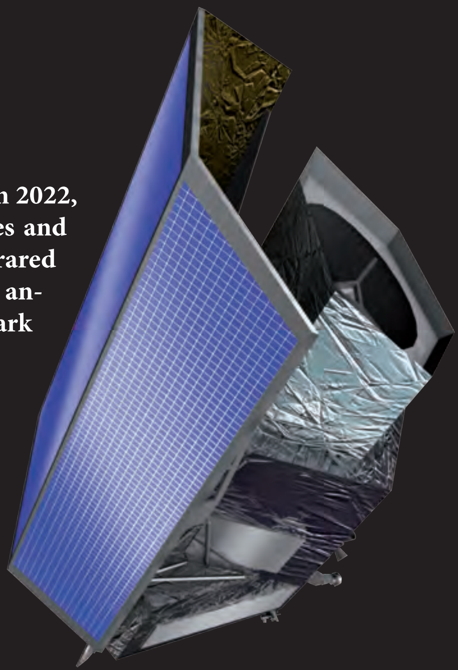
ESA's astrometry satellite Gaia is measuring the distance from Earth to more than a billion stars with unprecedented precision. The MPIA Gaia group leads the effort of using this data to reconstruct the astrophysical properties of those stars, played a key role in the data releases DR2 (April 2018) and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

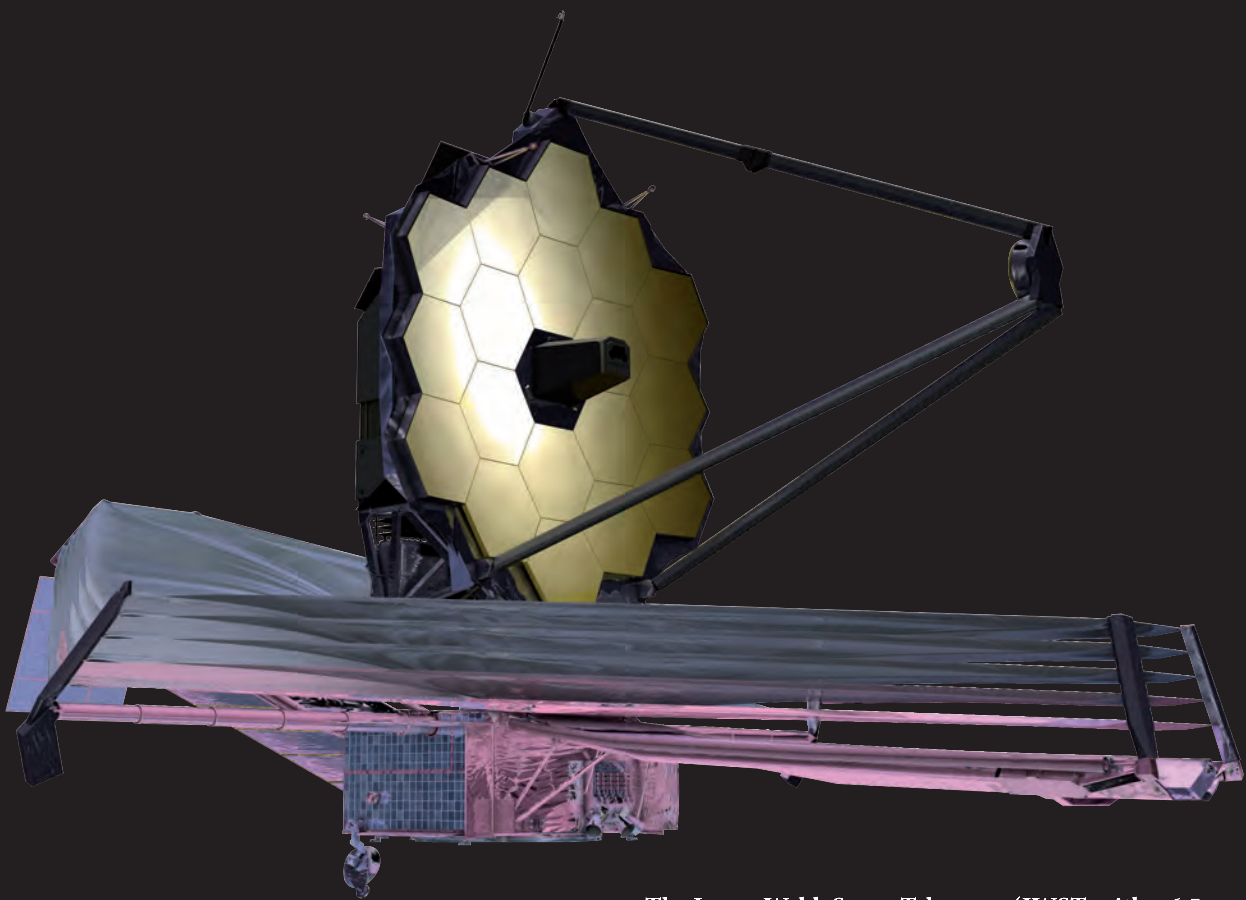




MPIA contributed to the construction of ESA's infrared observatory Herschel: We developed key components for the PACS instrument aboard the Herschel satellite, and were responsible for a number of observational programs undertaken with Herschel.

For ESA's Euclid mission, which is slated for launch in 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.

Credits: NASA, ESA

Major conferences organized by our staff members

Credit: C. Bailer-Jones / MPIA

Astronomical Time Series 2019
21–24 January
Haus der Astronomie, Heidelberg

Planetary dynamics
3–7 June
Haus der Astronomie, Heidelberg

STARPLANET2019
24–28 June
Ringberg Castle, Tegernsee

Discs2planets
9–13 September
Ringberg Castle, Tegernsee

Machine Learning Tools for Research in Astronomy
9–13 December
Ringberg Castle, Tegernsee

Fig. I.1: Participants of the meeting Astronomical Time Series in January 2019, in the Klaus Tschira Auditorium of Haus der Astronomie.

Fig. I.2: Participants of the Ringberg conference Machine Learning Tools for Research in Astronomy, in December 2019, which was dedicated to harnessing the tools of Machine Learning methods for analysis and discovery in observations and simulations.

Credit: D. Hogg / MPIA & CCA

Major Grants and Awards

Credit: T. Hartmann / MPG

Maria Bergemann

Credit: C. Hunt

Eduardo Bañados

Thomas Henning
received an ERC Advanced Grant worth 2.5 million Euros for research of young planetary systems, and was also elected an honorary member of the Hungarian Academy of Sciences.

Maria Bergemann
was awarded a Lise Meitner Research Group by the Max Planck Society. Her group will be based at MPIA.

Eduardo Bañados
received the German Astronomical Society's 2019 Ludwig Biermann Award. The award is conferred annually on an outstanding young astronomer.

Conchi Cárdenas Vázquez
was awarded the prize for the best Spanish PhD in Instrumentation, Computing and Technological Development in Astronomy and Astrophysics by the Spanish Astronomical Society.

Annalisa Pillepich
won the "Golden Spike Award" from the High-Performance Computing Center, Stuttgart (HLRS). Each year, the award honours the three most excellent projects that have performed computations on the center's clusters.

Leon Schädel
won the Max Planck Society's Trainee Prize.

The MPIA Precision Mechanics Workshop,
led by Armin Böhm, won the Max Planck Society's Vocational Training award, for the programme supervised by Stefan Meister.

Patzer Prizes 2018

Michael Rugel, MPIA
for his publication "Feedback in W49A diagnosed with radio recombination lines and models" (2019, A&A, 622, A4)

Daizhong Liu, MPIA
for his publication "Automated Mining of the ALMA Archive in the COSMOS Field (A3COSMOS): I. Robust ALMA Continuum Photometry Catalogs and Stellar Mass and Star Formation Properties for ~700 Galaxies at *z*=0.5-6" (2019, ApJS , 244, 40)

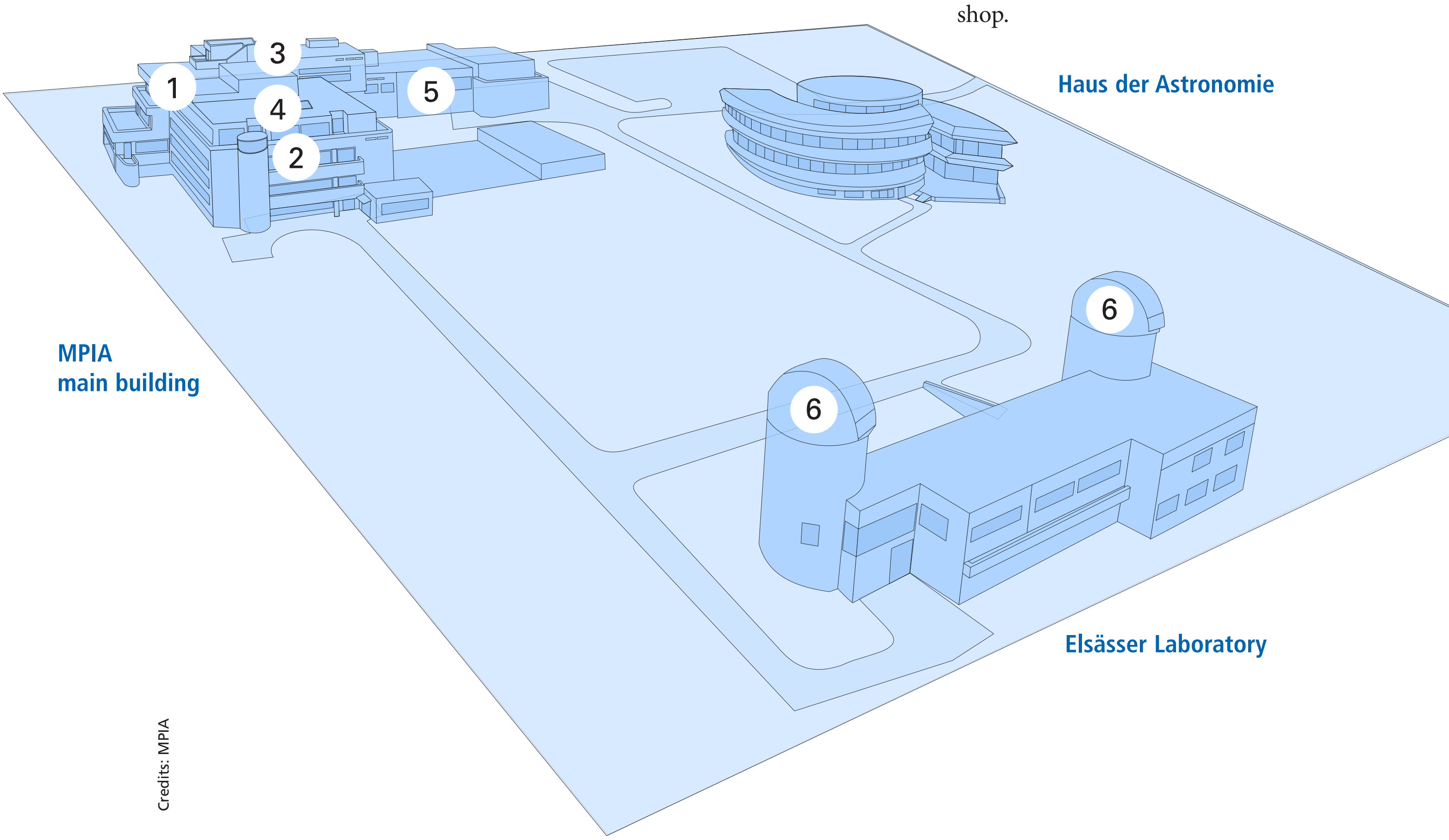
Irina Smirnova-Pinchukova, MPIA
for her publication "The close AGN reference survey (CARS): Discovery of global [CII] 158 μm line excess in AGN HE1353-1917" (2019, A&A, 626, L3)

Infrastructure

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

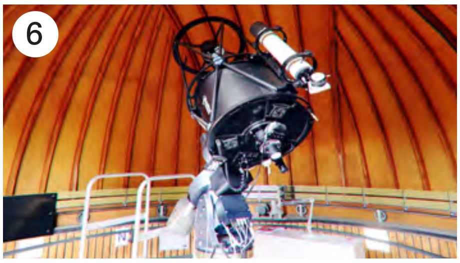
IT infrastructure capable of handling large amounts of data from observations and simulations.

Workshop, construction facilities and lab space, here a modern CNC milling machine in the Precision Mechanics workshop.



Two lecture halls and eight seminar/workshop rooms, here the small 2nd floor meeting room.

Experimental and assembly facilities including clean rooms for instrumentation.



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

People at MPIA

345

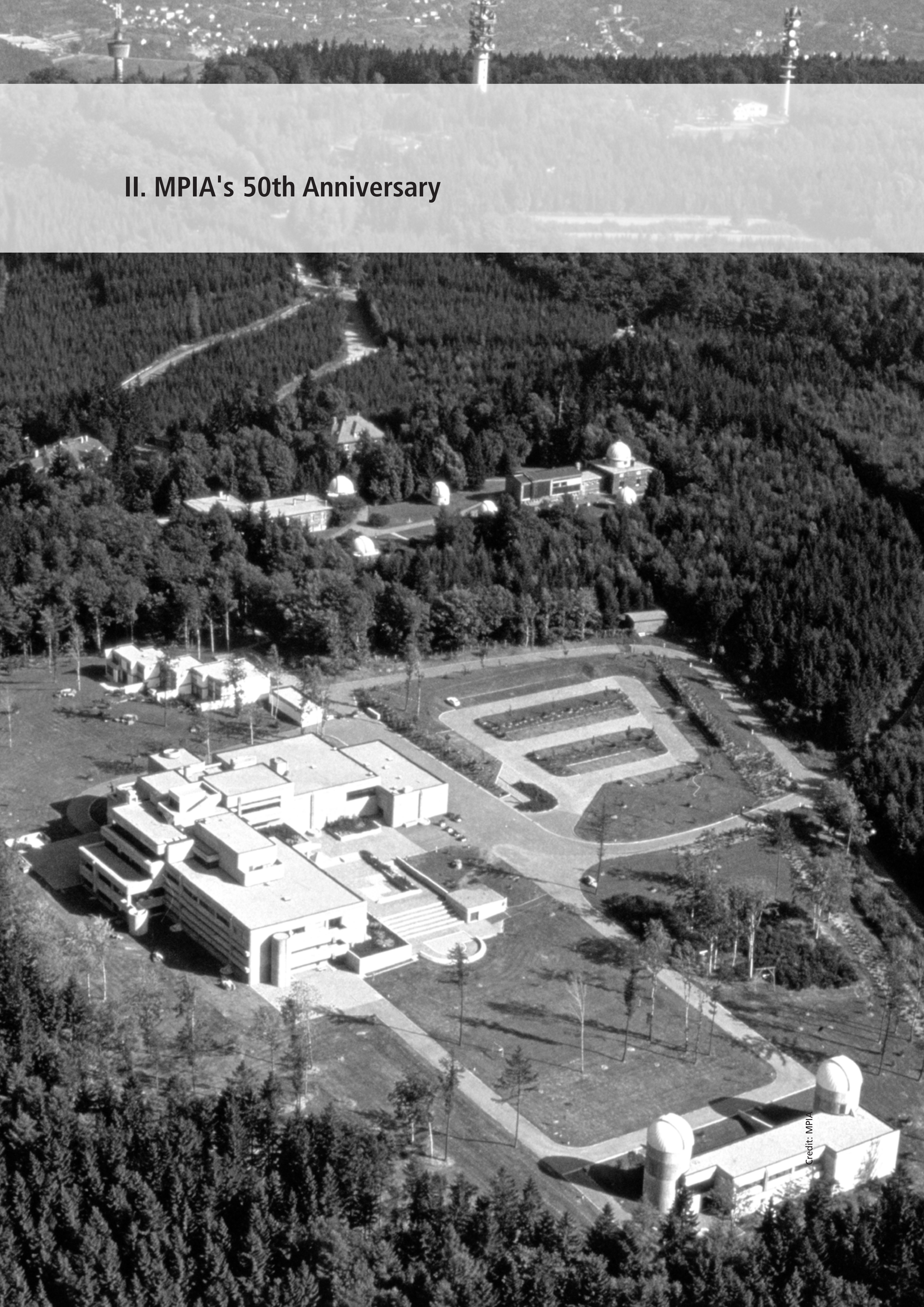
employees
keep the institute running.
208 of these are scientists,
including 102 junior scientists
or long-term visitors,
and 62 PhD students

7

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

Fig. I.3: MPIA's main building, with the Rhine valley in the background.

II. MPIA's 50th Anniversary



Credit: MPIA

II.1 Max Planck Institute for Astronomy

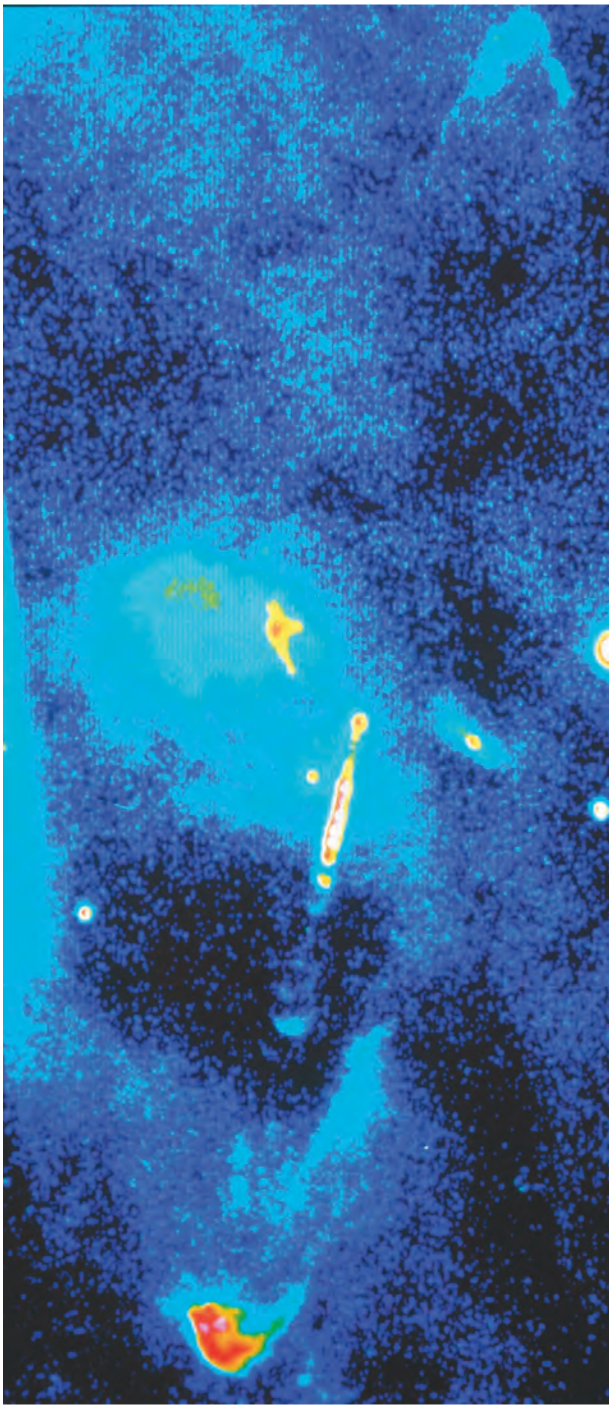
MPIA: The First 50 Years

In 1967, the Max Planck Society officially decided to establish a Max Planck Institute for Astronomy (MPIA). Less than two years later, in 1969, the first MPIA staff members began their work on Königstuhl in Heidelberg. In the fifty years that followed, MPIA developed into a prestigious research institute with an international reputation. The institute's 50th anniversary year was duly celebrated in September 2019 with an exciting live program in the historical Rococo Theatre in Schwetzingen.

How it all began

The original reason for founding the MPIA was rather unpleasant: At the beginning of the 1960s, astrophysical research in Germany was in rather poor shape. Lack of access to advanced observatories, of international collaborations and not least of adequate overall funding meant that astronomy research in Germany was far removed from the international leaders in the field at the time. In Germany itself, there were only smaller and insufficiently equipped observatories. And given the country's sub-standard observing conditions, even more powerful instruments would have been of little use. Since, overall, the number of large telescopes in the world during these years was much smaller than it is today, opportunities for collaboration were rare, and they were hampered further by a lack of travel funds. A "Denkschrift" White Paper commissioned by Deutsche Forschungsgemeinschaft (Germany's major science funding institution), published in 1962, documented this unsatisfactory situation in detail.

Wide-ranging consultations and discussions on how to improve the situation of astronomy in Germany led, among other actions, to the decision by the Max Planck Society on November 24, 1967, to found a Max Planck Institute for Astronomy (MPIA). The new institute was to be an important step towards bringing astronomy in Germany back to an internationally competitive level. Its initial mission was twofold: on the one hand, the institute was to coordinate the construction of a powerful large observatory abroad, which should provide direct access for researchers from Germany to top-level observations. On the other hand, of course, the institute was meant to become an outstanding research institution in its own right.



Credit: R. Mundt, T. Bührke, T. Ray

Fig. II.2.1: Early CCD image taken with the largest telescope on Calar Alto: bipolar jet of the young star Herbig-Haro 34, observed with the 3.5 m telescope. The colors correspond to different brightness values.

Credit: MPIA

Credit: MPIA

Credit: Atair-Foto, Madrid

Fig. II.2.2: ***Top:*** The construction site of the new institute building on the Königstuhl in the first half of the 1970s. Near the top of the image, the Landessternwarte is visible.
Left: Institute meeting in the new building. From left to right (in brackets the former responsibilities): Karl-Heinz Sorg (Head of Administration), Josef Solf (Spectroscopy, Bipolar Nebulae), Thorsten Neckel (Gamsberg, OB-Stars), Hans Hippelein (Fabry-Perot), Hans Elsässer (Director), Dietrich Lemke (THISBE, HII-Regions), Klaus Bahner (Telescopes), Christoph Leinert (HELIOS, Zodiacal Light), Ronald Weinberger (Bipolar Nebulae).
Right: Calar Alto Observatory in southern Spain after the completion of all telescopes in the 1980s. From left to right: Spanish 1.5 m telescope, Schmidt telescope, 1.23 m telescope, 2.2 m telescope and 3.5 m telescope.

Two years later, in February 1969, the first members of the institute's staff, under founding director Hans Elsässer, reported to work on the Königstuhl mountain in Heidelberg. Initially, MPIA had temporary offices in the buildings of the Landessternwarte (the nearby State Observatory, which has since become part of the University of Heidelberg). In parallel, the institute's own building was under construction just a few hundred meters away.

In May 1976, the building was officially opened. In parallel, construction crews had already been busy establishing MPIA's major observatory in Southern Spain: With Calar Alto Observatory, parts of which would be under construction until the mid-1980s, German astronomers finally had a state-of-the-art observatory at their disposal. Telescopes with mirror sizes of up to 3.5m, built in cooperation with Zeiss and Schott, allowed the institute to conduct cutting-edge observations. In addition, a 2.2m telescope – largely a twin of one of the Calar Alto telescopes – was built for observations in the Southern hemisphere, and put finally into operation, at the La Silla site of the European Southern Observatory (ESO) in Chile. This instrument, now known as the ESO/MPG 2.2m telescope, is still active today. Originally, it had been intended for the Gamsberg mountain in present-day Namibia, as a powerful MPIA-owned observatory in the South. But this location was ultimately rejected for political reasons.

Steps to international top research

Already in the 1970s, with initial balloon observatory experiments, MPIA set its sights on astronomical observations that would leave significant parts of Earth's atmosphere behind. This development directly led to MPIA participation in the construction of space-based infrared telescopes. A first highlight in this area, in the mid-1990s, were important hardware contributions to ESA's Infrared Satellite Observatory ISO. At that time, MPIA was already playing an increasingly important role in the field of infrared astronomy, both scientifically and regarding the development of custom-made instrumentation. Looking back, this made the institute an "early adopter" of the multi-wavelength approach that is a staple of modern astronomy.

Among the significant scientific discoveries made at that time were the detection of fast particle streams (called jets) emitted by young stars, the characterization of some active and ultra-luminous starbursting galaxies that glow strongly in infrared light, and the first complete survey of double stars in the Taurus star formation region.

A number of key topics from the early days of the MPIA can be traced right to their present-day counter-

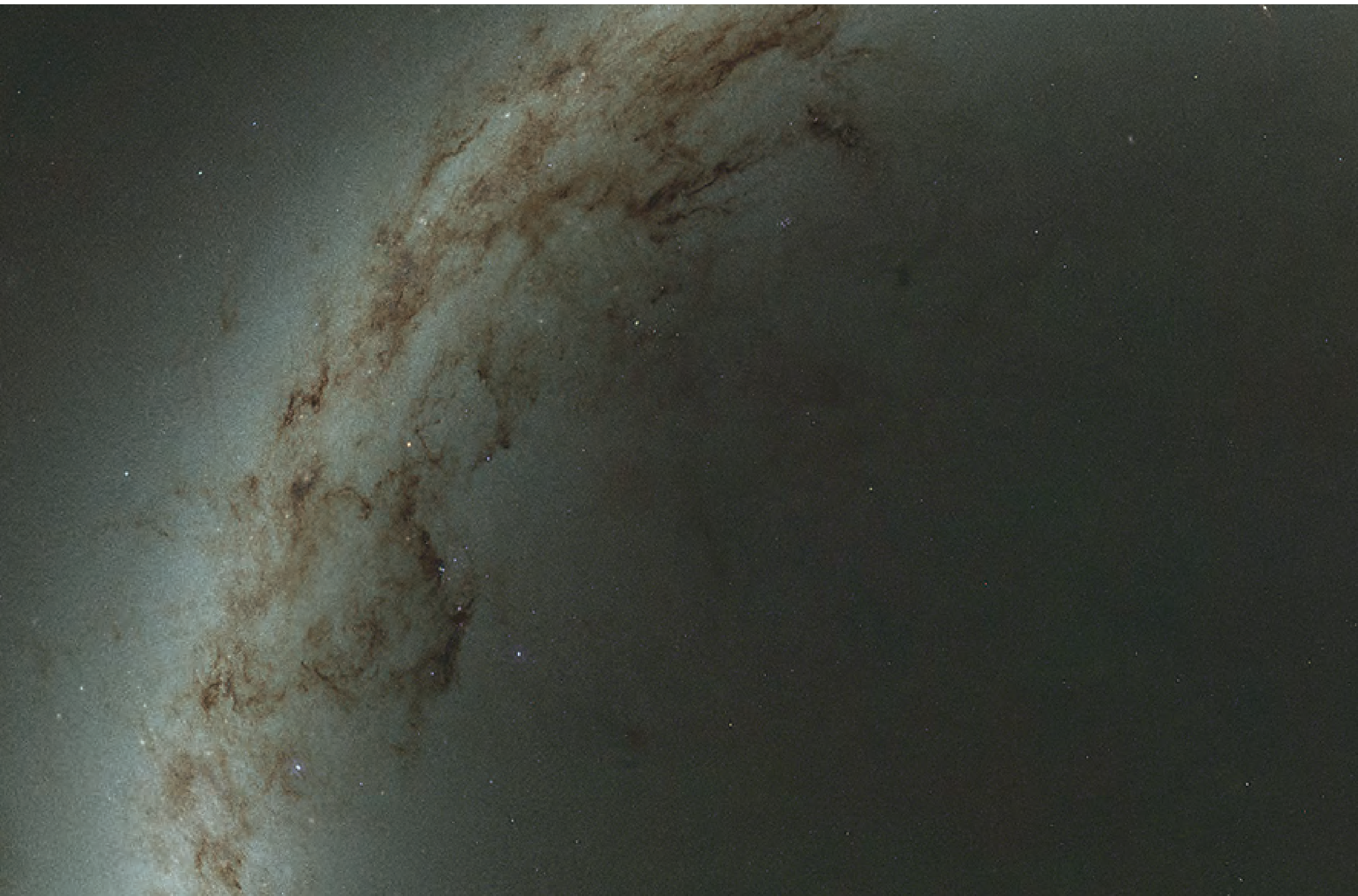


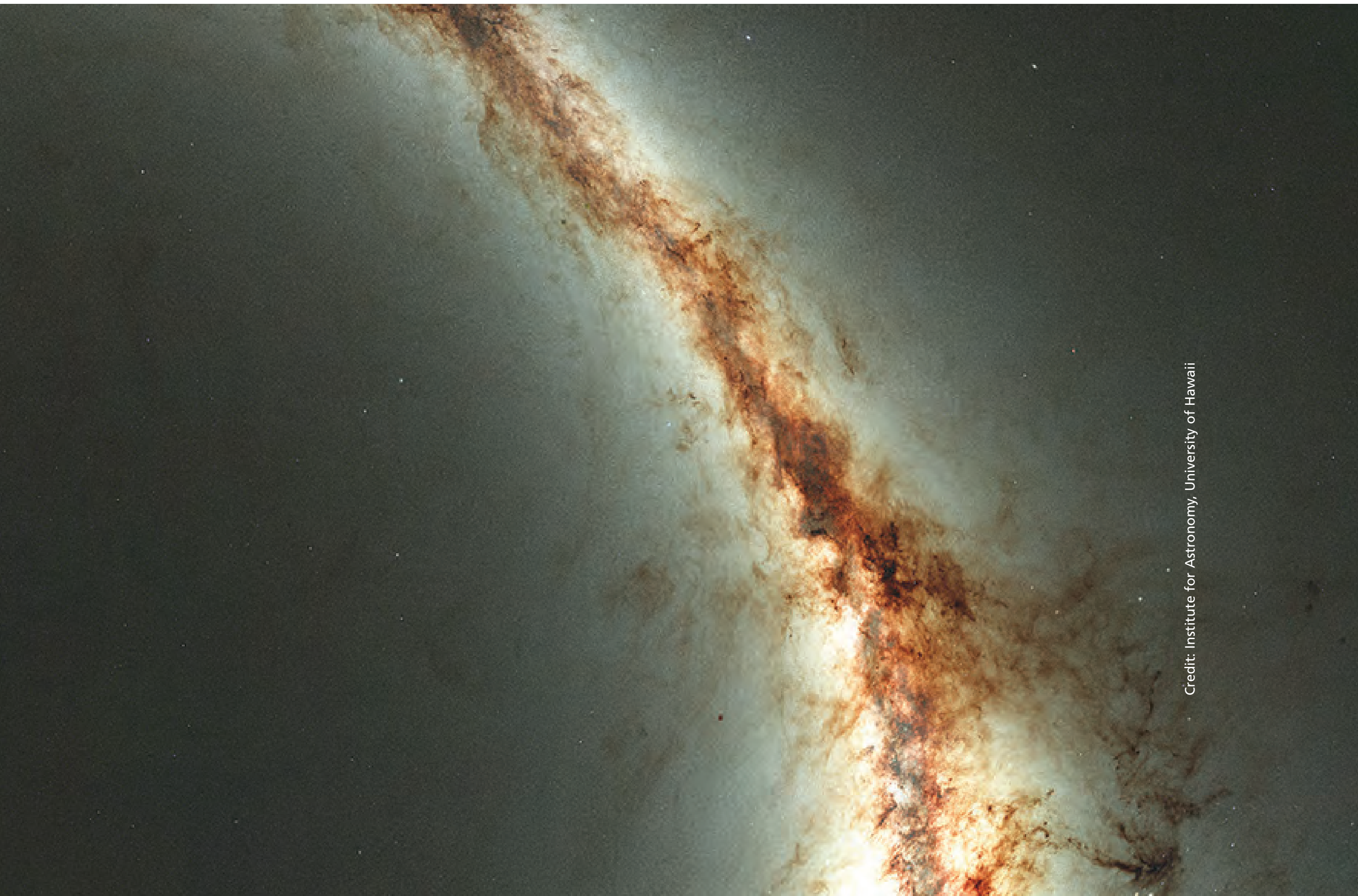
Fig. II.2.3: Mosaic from a large number of images from the Pan-STARRS survey - an example of modern data sets which, in conjunction with other surveys (such as Gaia) or observations at other wavelengths (such as with ALMA or the VLA), are also used at MPIA to investigate the structure of the Milky Way system or star formation.

parts. Currently, MPIA has three scientific departments – the longtime departments led by Thomas Henning and Hans-Walter Rix, respectively, and since 2020 a new third department led by Laura Kreidberg. Within that framework, MPIA researchers investigate the formation of planets and stars and the nature of extrasolar planets (such as their atmospheres), as well as the formation and evolution of galaxies in a cosmological context and, linked to this, the structure of our home galaxy, the Milky Way system. To explore these scientific areas, MPIA not only uses the largest and most modern ground-based or space-based observatories for research in many different spectral ranges. Rather, the institute is involved in the development and construction of the instruments for these observatories in international collaborations and is an internationally renowned address, especially for infrared experiments and the equipment for high-resolution observations using adaptive optics and interferometry.

Recent developments

Over the past 50 years, instrumentation has continued to play an important role in the institute's overall development. Major projects include hardware and software contributions to ESA's Herschel Space Telescope and to instruments at the Very Large Telescope (VLT/VLT Interferometer) of ESO in Chile. More recently, the institute contributed to instruments for the new James Webb Space Telescope being built by NASA and ESA, and development work is already underway for several instruments for the world's largest telescope currently under construction: ESO's Extremely Large Telescope (ELT), with a main mirror 39 meters in diameter. This remarkable telescope will be located in the Atacama Desert in Chile and is scheduled to begin operations in the mid-2020s.

Scientific successes of recent years include the spatial resolution of protoplanetary disks around young stars in which planets form, and of the torus-like structures around active supermassive black holes at the centers of galaxies. MPIA has also contributed to the considerable progress that has been made in the exploration of the structure of our home galaxy, the Milky Way system – with the discovery of numerous small satellite galaxies, as well as with the co-organization and analysis of extensive surveys such as the famous Sloan Sky Survey or of data from ESA's astrometry satellite Gaia. Another exciting current field of research is the discovery and characterization of exoplanets, that is, of planets that orbit stars other than the Sun. MPIA has been particularly successful in producing direct images of such planets and in measuring their atmospheric spectra – two of the newest and most challenging areas of modern observations. This success is tied directly with the institute's instrumentation projects, notably the high-resolution SPHERE instrument for the VLT, which is equipped with outstanding adaptive optics. All of these successes are also important steps towards the possible detection of life on other planets.

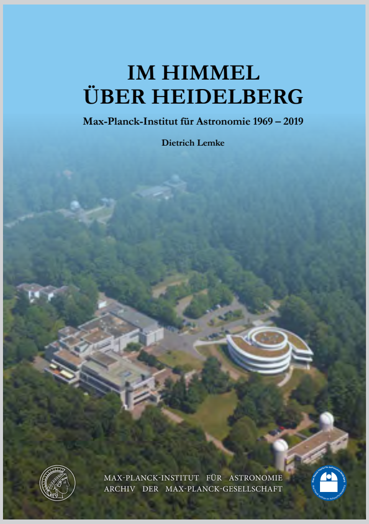


Credit: Institute for Astronomy, University of Hawaii

Popular with young researchers and the public

The fact that, over the past 50 years, the Max Planck Institute for Astronomy in Heidelberg has developed into a research institute of international visibility has had collateral benefits. MPIA has been and continues to be an important part of the careers of numerous young scientists from all over the world – undergraduates, doctoral students or postdoctoral researchers. Since 2005, the institute's close ties to the University of Heidelberg have been given a formal structure by the International Max Planck Research School (IMPRS-HD), which has become the framework for all doctoral studies of Heidelberg's university-based and extra-mural astronomical institutes. More than 70 former MPIA researchers have moved on to hold professorships around the world.

A further milestone on the MPIA campus was the opening of Haus der Astronomie (literally “House of Astronomy,” HdA) in 2011. HdA is a center for astronomy education and research operated by MPIA. The galaxy-shaped HdA building was built by the Klaus Tschira Foundation (KTS); additional partners are Heidelberg University and the City of Heidelberg. Since then, educational and outreach activities as well as scientific exchange – all of which have a long tradition on the Königstuhl – have intensified considerably. The building is also home to the editorial staff of the popular magazine Sterne und Weltraum (literally “Stars and Space”) published by Spektrum-Verlag. That magazine was co-founded in 1962 by the first director of the MPIA, Hans Elsässer!



Dietrich Lemke: Im Himmel über Heidelberg: Max-Planck-Institut für Astronomie 1969–2019

Herausgegeben vom MPIA und vom Archiv der Max-Planck-Gesellschaft, Berlin und Heidelberg 2019

If you are interested in details of the 40 years of MPIA history, and able to read German, then “Im Himmel über Heidelberg” is for you. The book was written by Dietrich Lemke, who was one of the first five full-time employees hired by founding director Hans Elsässer starting February 1969. Until his retirement in late 2005, Lemke led the Infrared Space Observatories group at the institute. On 487 pages and with many illustrations, Lemke's book traces not only MPIA's history from the beginnings to 2019, but also provides an account of the 400-year tradition of astronomical research in the Electoral Palatinate region in general, and a handy guide to astronomical sightseeing in the Heidelberg region. The original version of the book was published in 2009, and the present, revised, second edition in time for the anniversary year 2019.

Dietrich Lemke, Thomas Henning: Astronomische Streifzüge durch Heidelberg

Morio-Verlag Heidelberg 2021

For a shorter survey of Heidelberg’s astronomical history, again in German, we recommend this book by Dietrich Lemke and MPIA director Thomas Henning. The “Astronomical strolls through Heidelberg” present not only the city’s history, which in astronomy goes back to the printing of Kepler’s “Astronomia Nova” in 1609, but also the current astronomical institutes, major actors and benefactors who had an impact on astronomy, and an overview of the various parts of astronomy that are currently under investigation.

HISTORICAL MPIA IN NUMBERS

13

Number of MPIA employees in 1969. Has since grown to more than 300.

30

kilometers –
length of the new Calar Alto access road (1973).

11500

visitors
at MPIA's first Open Day in 1979.

163840

pixels (512 x 320)
in MPIA's first CCD camera in 1980, for the 2.2 m Calar Alto telescope.

60

cm mirror diameter
of the ISO infrared observatory, launched in 1995.

II.2 Max Planck Institute for Astronomy

Celebrating 50 Years of MPIA

Fig. II.2.1: The anniversary event on September 20, 2019 in Schwetzingen Castle starts with an audiovisual "fireworks" presentation – a video trailer as a homage to 50 years of MPIA.

Anniversary celebration in Schwetzingen

Together with invited guests from the world of science as well as from other reaches of society, MPIA staff celebrated the institute's 50th anniversary in style on September 20, 2019. The venue was certainly stylish: in the Rokokotheater, the magnificent theater built by Prince Elector Carl Theodor as part of Schwetzingen Palace in the mid-18th century, several hundred guests attended an entertaining live event, which deliberately avoided the stuffy character of other anniversary events, with their string of formal speeches and greetings. Instead, a varied, sometimes surprising and often tongue-in-cheek program awaited the guests, moderated by Klaus Jäger and Natalie Fischer, and featuring not only speakers with a special connection to the institute, but also inhouse video productions and live music. After the almost three-hour, but entertaining event, the excellent weather made it possible to celebrate not only in Schwetzingen Palace, but also in the palace gardens.

Guests were issued with goodie bags containing, among other things, a high-quality 2020 calendar with remarkable astronomical images from 50 years of successful MPIA work, which was produced with the support of Heidelberger Druck AG, and a new edition of Dietrich Lemke's book "Im Himmel über Heidelberg" (literally "In the sky above Heidelberg") about the history of astronomy in and around Heidelberg, published by the institute jointly with the Archive of the Max Planck Society.

In a very special way, the celebration closed an historical loop: In 1764, the first astronomical observatory in the Rhein-Neckar region was erected on the roof of Schwetzingen Palace, for the use of the Prince-Electors court astronomers.

Fig. II.2.2: ***Top left:*** The first of a total of three outstanding keynote presentations was given by Ewine van Dishoeck (Leiden University) on the topic "Our Origins in Space". She was also a member of the MPIA's Advisory Board for several years. ***Top right:*** Rolf-Peter Kudritzki, long-term chair of MPIA's Scientific Advisory Board (Fachbeirat), was another lively speaker at the event. ***Center:*** Between the contributions there was live music with Martin Kürster and Klaus Jäger - as accompaniment to a total of three other movies, in which the history and the various activities of the MPIA were presented. ***Bottom left:*** Natalie Fischer and Klaus Jäger, who are currently presenting the anniversary calendar and the new edition of Dietrich Lemke's book, led through the event. Afterwards, the audience was able to take a copy of both printing works with them as a souvenir. ***Bottom right:*** Closing words by MPIA Director Thomas Henning, who warmly thanked all the active participants for the nice event. Special thanks went to those who had conceived and organized the show - Klaus Jäger, Natalie Fischer, Martin Kürster, the MPIA Secretaries (Marina Gilke, Carola Jordan, Susanne Koltes-Al Zoubi, Heide Seifert) and other active supporters from within the Institute and from outside.

Credits: Uwe Anspach, page 27 center: M. Pössel / MPIA

Fig. II.2.3: Speech in praise of the institute by the Vice President of the Max Planck Society Ferdi Schüth.

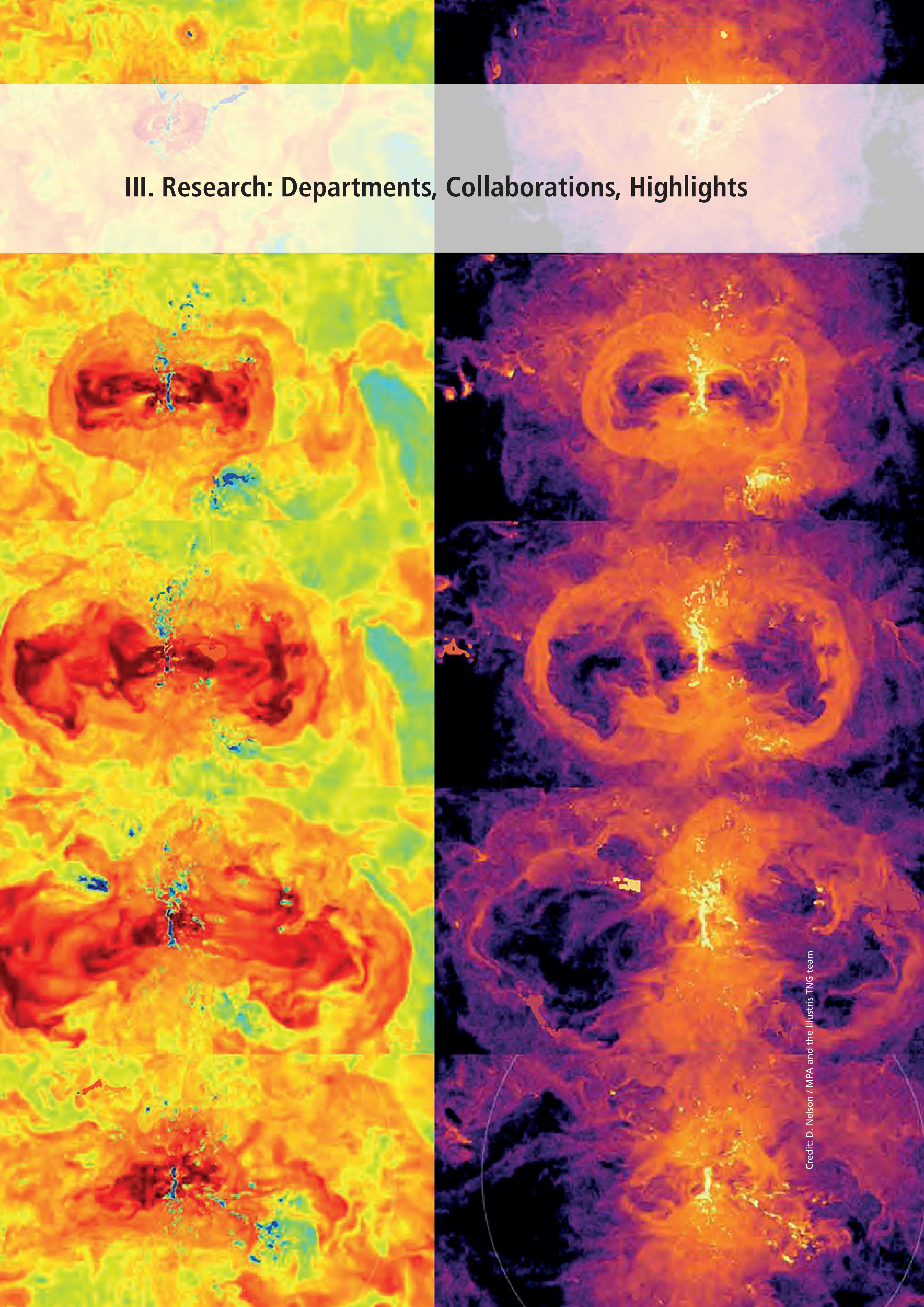
Fig. II.2.4: Afterwards Steven Beckwith from the University of California/Berkeley gave a presentation about "Invention and Discovery in Astronomy". He was one of the former directors of MPIA and still visits the institute regularly.

Fig. II.2.5: ***Middle:*** MPIA's Managing Director, Hans-Walter Rix, welcomes the audience to the Schwetzingen Rokoko Theater. ***Left:*** Greetings from former ESA astronaut and Chairman of the MPIA Board of Trustees Reinhold Ewald from the University of Stuttgart. ***Right:*** General amusement was provided by the small, not entirely serious gifts that the presenters had thought up for all the active people on stage. They all had a connection to the activities of the respective person. Here Ferdi Schüth is given a bag of charcoal – appropriate for the director of the MPI for Coal Research.

Fig. II.2.6: The party continued into the evening in the foyer of the theater and in the park – accompanied by the Tante Hilde Brass Band

Credits: Uwe Anspach

III. Research: Departments, Collaborations, Highlights



Credit: D. Nelson / MPA and the Illustris TNG team

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

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

Credit: ESO

Fig. III.1.1: Massive star clusters like the one in this image, NGC 3603 are born when giant clouds of gas and dust collapse. As they do so, a cascade of fragments forms, with many of the fragments giving birth to a star. In 2019, MPIA's Henrik Beuther and colleagues published observations of the star formation region G351.77-0.54 in the Southern constellation Scorpius, taken with the ALMA observatory. Their study shows that the mechanisms for fragmentation are fairly straightforward, resulting from the combination of the cloud's pressure and gravity. More complex features, such as magnetic lines or turbulence, play a smaller role than previously thought.

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, and ESO's Extremely Large Telscope, which should commence science operations in 2026.Observations with these telescopes provide insights into the physics and chemistry of the interstellar medium and the earliest stages of star and planet formation, and allow MPIA scientists to discover and characterize exoplanets.

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

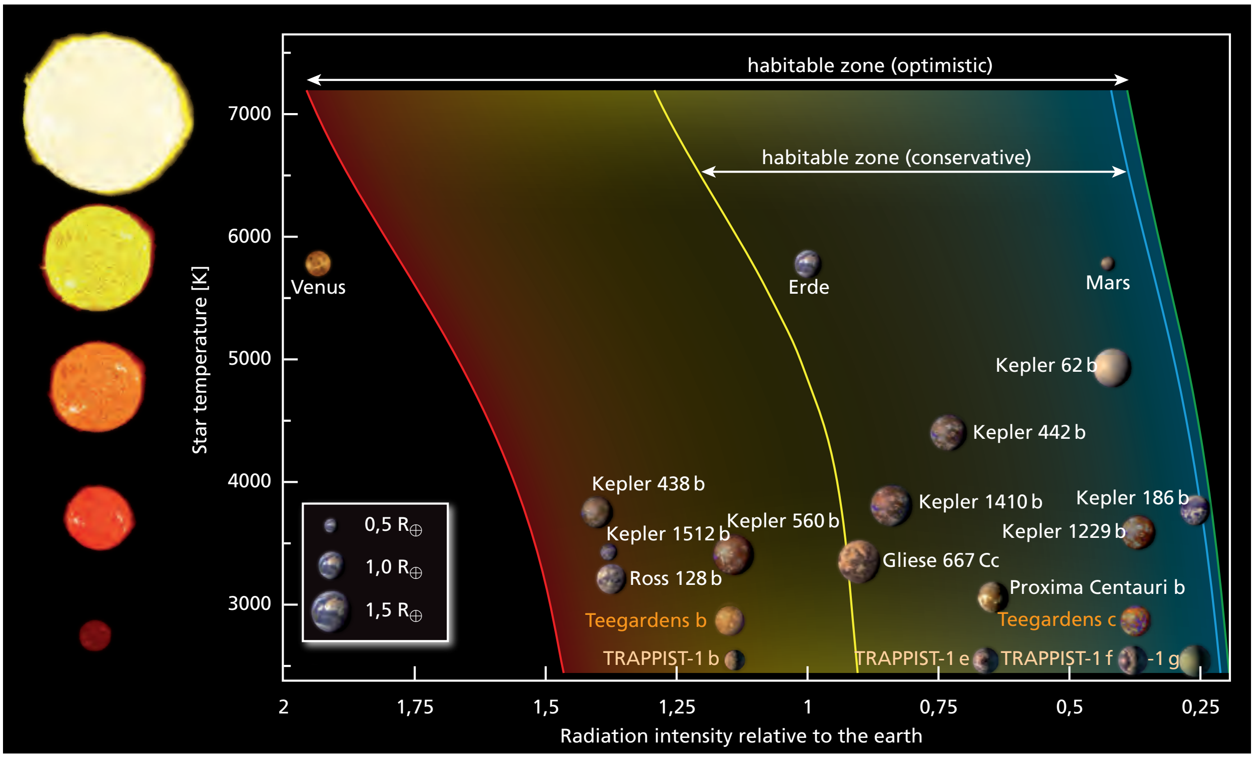
The PSF department is involved in several programs that rise to this considerable challenge. Take, for instance, adaptive optics, a technique to compensate for the distortions of astronomical images by the Earth's atmosphere, allowing large telescopes to reach particularly high resolution. Or interferometry,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

Understanding the origin of stars

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

And more specifically: To what extent does the probability for the formation of a star of a given mass depend on the mass of the star-forming cloud? This leads to the

Fig. III.1.2: An international team of astronomers that includes MPIA's Martin Kürster has found two Earth-like planets around one of the smallest known stars, which is called "Teegarden's star." The planets, which orbit in the star's habitable zone where liquid water is possible, are only a quarter and a third more massive than the Earth, respectively.



Credit: C. Harman

more general question of which properties of the cloud determine the outcome of the star formation process. Key open questions concern the role of magnetic fields and turbulent flows in controlling the onset of star formation – with direct consequences for the initial mass function and the duration of the star formation process.

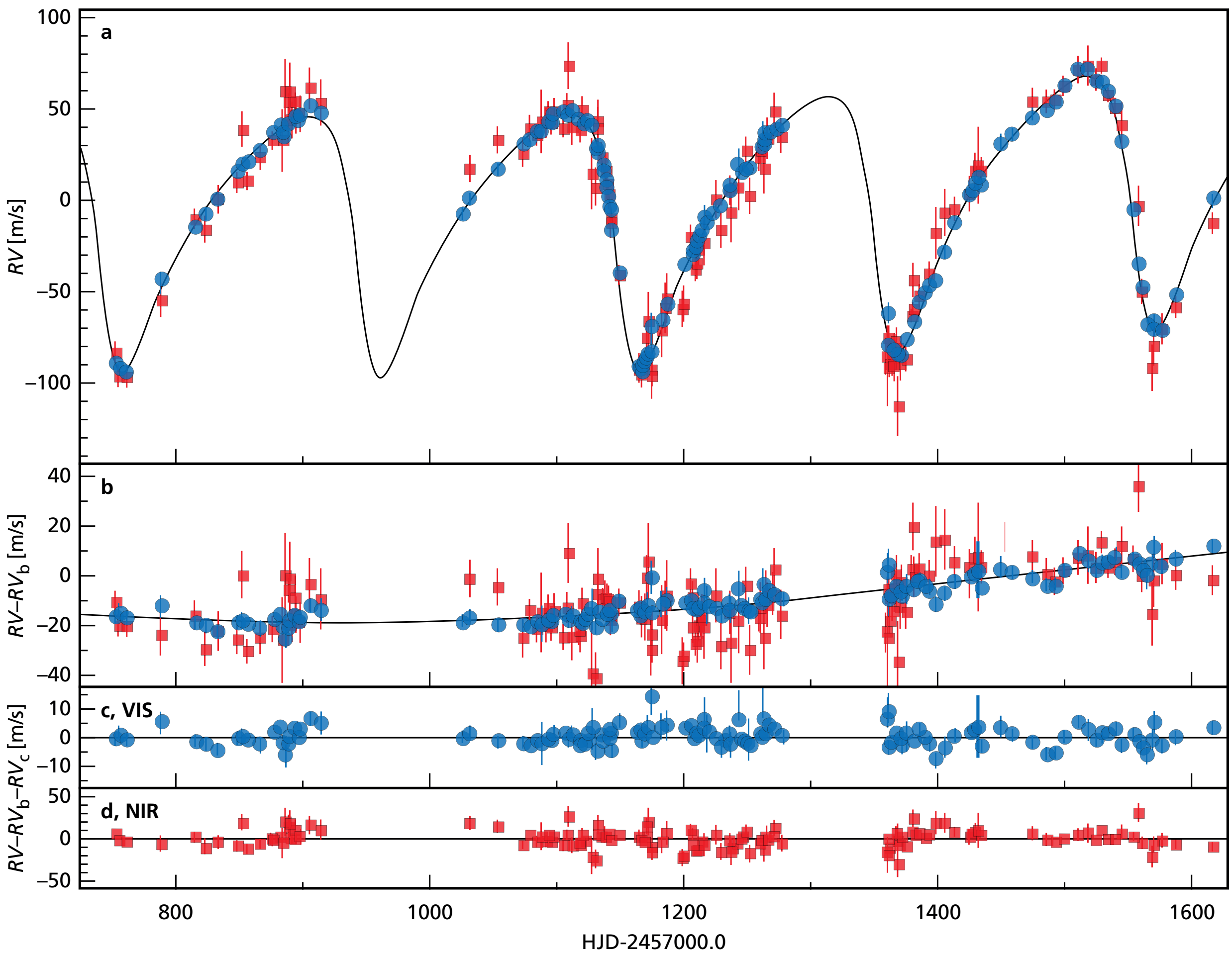
In general, collapsing individual cloud clumps will fragment to form binary stars or multiple systems. At the high end of the mass scale, the formation of very massive stars takes place in clusters, which makes for exceedingly complex star formation environments and strong feedback processes. The rapid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

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

A peek behind the curtain

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

Fig. II.1.3: Research on exoplanets can give important input to studies of planet formation. A planet around the star GJ 3512 with the radial velocity method by a group of astronomer that includes researchers from the PSF department proved to have an unusually large mass relative to its host star, challenging a widely accepted model of planet formation. Panel a illustrates how the radial velocity of GJ 3512 (vertical axis) changes with time indicated in days since 8 December 2014, 12:00 p.m. UT (Universal Time, horizontal axis). HJD stands for Heliocentric Julian Day. Both the visual (blue symbols) and the infrared (red symbols) channels agree well. The black solid curve is the best orbital fit to the data. After subtracting the contribution of GJ 3512 b, panel b shows the residual, which indicates the presence of a long-term period hinting to a second planet. Panels c and d depict the residuals of the best overall orbital fit for the two CARMENES channels.



Credit: Morales et al. (2019)/MPIA

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

Observing from the ground and from space

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

Presently, a strong focus of the department's work is on preparing projects in the field of star formation, protoplanetary disks, and exoplanets for the James Webb Space Telescope (JWST), the designated successor of the Hubble Space Telescope. The JWST 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 large instrumentation project, we are looking towards the largest ground-based telescope yet: The PSF department will provide the camera and adaptive optics system for METIS, the mid-infrared instrument for the Extremely Large Telescope, a 39 meter telescope currently under construction in Chile.

Planet formation and the search for exoplanets

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

PSF astronomers are heavily involved in observing programs to search for extrasolar planets through direct imaging, the transit technique and radial velocity observations of objects discovered with the Transiting Exoplanet Survey Satellite (TESS). The HATSouth transit network, with its three stations in Australia, Chile and

Fig. II.1.4: Submillimeter antennae like the ones shown here, the NOEMA observatory in the French Alps, are particularly suited to detecting continuum radiation from cold cosmic dust. Using this kind of measurement, the large programme CORE, which is led by MPIA scientists from the PSF department, studies the formation of disks during the early evolutionary stages of massive star formation.

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

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

Star and planet formation in a computer

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

A versatile program has been launched to link planet formation with the properties of planets and their atmospheres in preparation for the analysis of the planetary spectra that will be obtained with JWST.

Linking the cosmos and the laboratory

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

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

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. As part of this initative, MPIA has established new Origins of Life laboratories, with the goal of investigating the formation of pre-biotic molecules under conditions typically found on comets and the parent bodies of meteorites.

III.2 Departments

Galaxies in their Cosmological Context – The GC Department

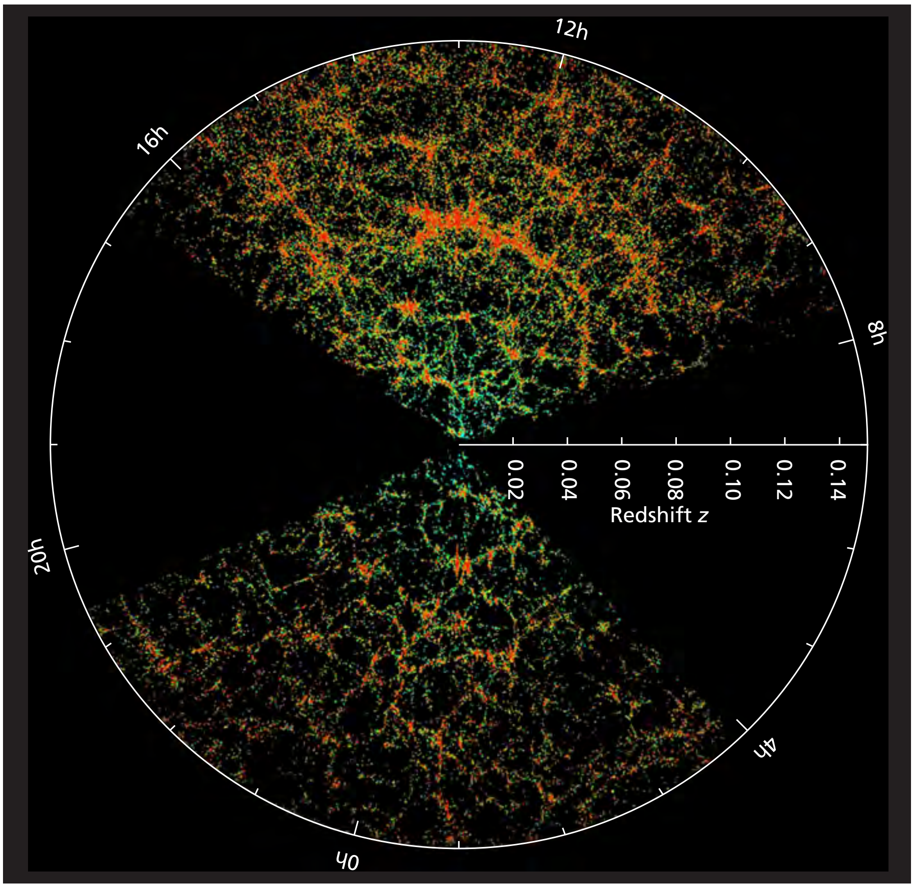
Director: Prof. Dr. Hans-Walter Rix

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 cosmic 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 of the overall hierarchical structure of the cosmos.

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



Credit: M. Blanton and SDSS

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

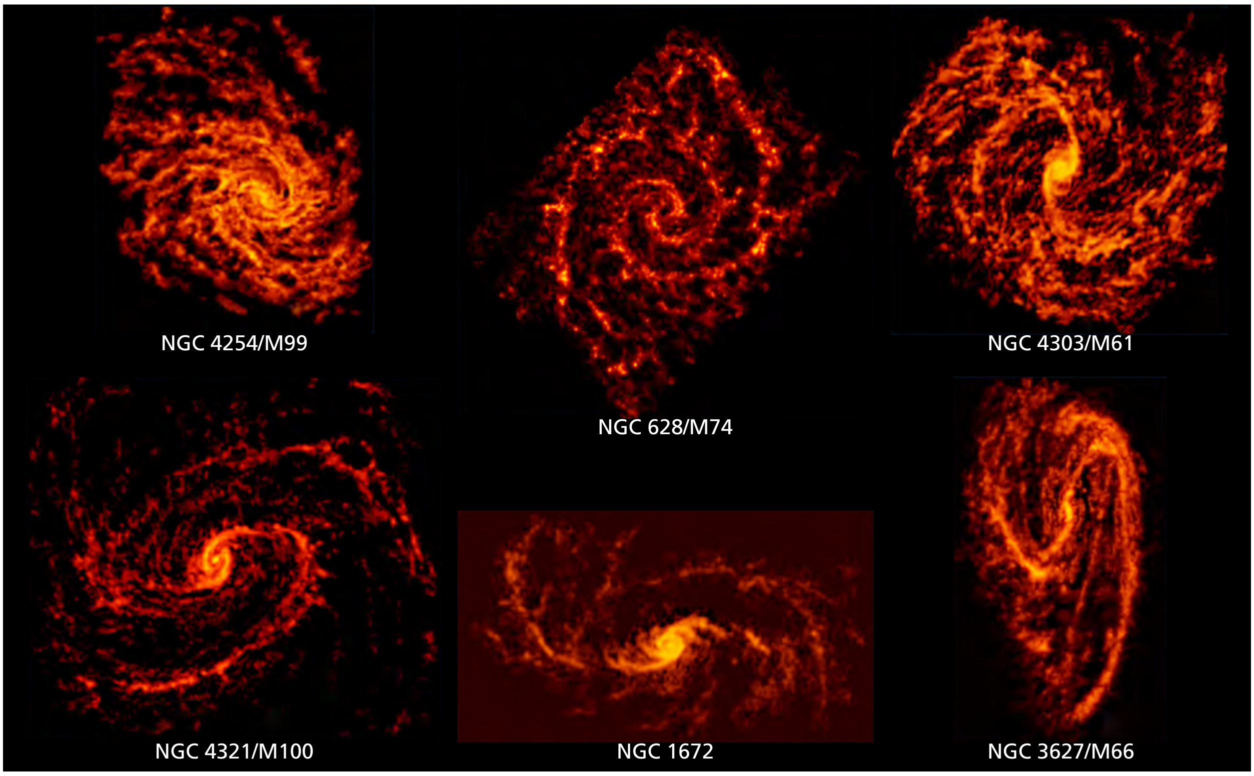
Emerging order in the realm of galaxies

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

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

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



Credit: ALMA (ESO / NAOJ / NRAO); NRAO / AUI / NSF, B. Saxton

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

hydrogen molecules H_2. But most of the gas in the Universe is not part of any galaxy. Throughout the history of the Universe, the lion's share of gas has always resided in between galaxies, forming the intergalactic medium.

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

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

Fig. II.2.3: This artist's impression shows two tiny but very dense neutron stars at the point at which they merge and explode as a kilonova. In 2019, a group of astronomers that includes MPIA's Camilla Juul Hansen conclusively demonstrated that neutron star mergers provide the right conditions for the so-called r-process: The rapid capture of neutrons by atomic nuclei, which is considered the process by which elements heavier than iron are formed.

The Milky Way, a model organism for understanding galaxies

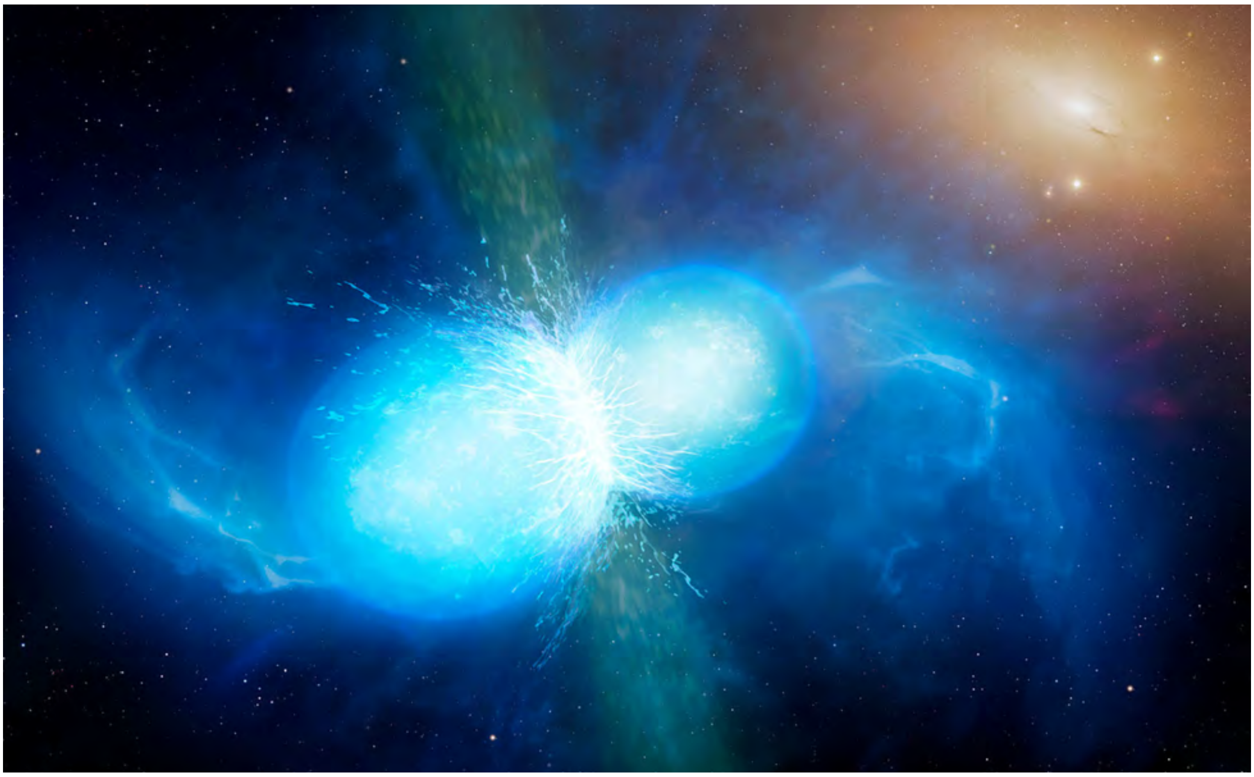
Our own galaxy is very average, making it eminently suitable as a test case for understanding the more general physical mechanisms at work in shaping galaxies. Our Galaxy is, of course, absolutely exceptional with respect to the detail in which we can study it: we can now observe it in 3D, determining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

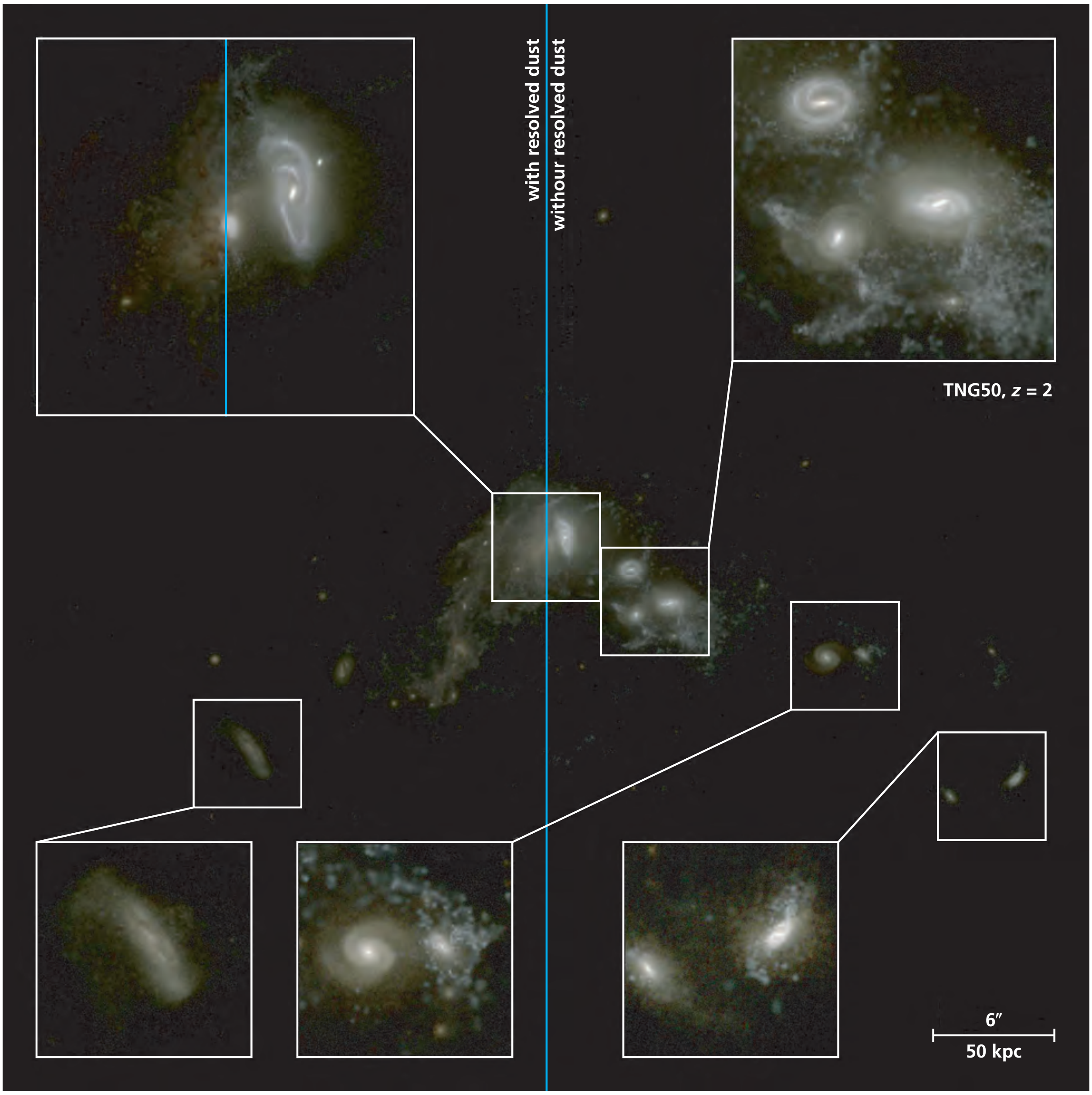
Asking the right questions

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



Credit: University of Warwick / M. Garlick / ESO



Credit: TNG Collaboration

Fig. II.2.4: In simulations like TNG50, it is possible to follow the evolution of a model universe from the Big Bang to the present. This image shows the optical light from stars within a forming protocluster of galaxies at redshift two in the TNG50 simulation. The impact of a sophisticated post-processing model for dust absorption and scattering (on the left) is contrasted against the intrinsic light that the stellar populations emit (on the right). Each of the zoom-in panels show individual galaxies marked within the larger field of view.

into galaxies, to be processed there into new stars? In turn, how does it get expelled from galaxies? And when and where does gas get converted from atomic to molecular, in order to be ready to form stars? Or, to bring up a more general question about the relationship between galaxies and dark matter's cosmic web: which kinds of galaxies reside in dark matter halos of different size?

The process of star formation on the scale of galaxies 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.

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

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

Collaborations and initiatives

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

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

III.3 Departments

Atmospheric Physics of Exoplanets (APEx)

Director: Dr. Laura Kreidberg

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

Characterising diverse atmospheres

Now that this diverse population has been uncovered, the next step is to characterise the planetary atmospheres in detail. The atmospheric physics and chemistry hold the keys to the planets' formation and evolutionary histories,

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

Credit: L. Kreidberg

present-day climate, and even habitability. For gas giant planets, the atmospheric chemical composition provides a record of the formation conditions in the disk, including the distance from the host star. For intermediate size planets, knowledge of the atmospheric composition reveals whether the planets are more like super-Earths, with large rocky cores, or mini-Neptunes, with a large fraction of water ice. Finally, for terrestrial worlds with rocky bulk compositions like the Earth, the detection of an atmosphere can teach us how the planet evolved over billions of years, and how the initial chemical inventory was influenced by volcanic activity, atmospheric escape, and the possible presence of life.

Over the past few years, MPIA has been keen on expanding in this interesting direction, in the form of a new, third scientific department. In the fall of 2019, that plan met with the approval of the Max Planck Society, leading to the foundation of the new APEx department, headed by MPIA's new director Laura Kreidberg (Fig. III.3.1), in spring 2020. APEx now provides a unique opportunity to assemble a critical mass of exoplanet characterisation experts in a single place. The department will grow over the coming years to include in-house experts on exoplanet observations, theory, and instrumentation development.

A diversity of challenges

Exoplanet atmosphere characterisation provides major challenges on multiple fronts: from pushing detectors beyond their design limits to search for the tiny signal of atmospheric absorption, to modelling atmospheric physics and chemistry over orders of magnitude in time and distance. Tackling these challenges requires close collaboration between experts, and progress in the field will be greatly accelerated with an entire department devoted to these topics.

Already, APEx astronomers are leading observing and modelling initiatives with state-of-the-art facilities and tools. These include Hubble and Spitzer observations of lava worlds and ultra-hot Jupiters, interpretation of some of the first exoplanet spectra directly measured by K-band interferometry, and 3D modelling of atmospheric dynamics. A recent highlight is a measurement of the first thermal phase curve for a terrestrial world, the hot rocky planet LHS 3844b (shown in Fig III.3.2). The large day-night temperature contrast for this planet

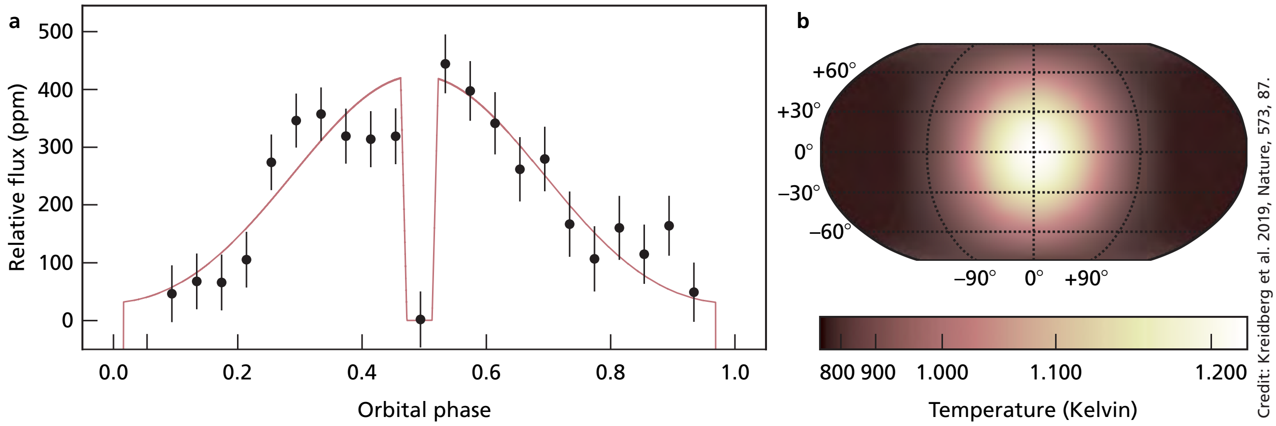


Fig. III.3.2: The thermal phase curve of the hot rocky exoplanet LHS 3844b measured with the Spitzer Space Telescope (left), and the inferred temperature map (right). The large temperature contrast between the dayside and nightside suggests that this planet has no atmosphere, and instead we are seeing heat emanating directly from the rocky surface. The temperature of the surface is consistent with expectations for a dark rock, like basalt, which is suggestive of widespread volcanic activity in the planet's past.

suggests that there is negligible atmospheric heat redistribution, and we are most likely seeing all the way down to the planet's rocky surface. APEx scientists are looking forward with great anticipation to the launch of the James Webb Space Telescope, expected for fall 2021, which will open the door to studying a wider variety of planets in greater detail than ever before. Laura Kreidberg will lead a team to analyse some of the first Webb data, through her collaboration with the Transiting Exoplanet Community Early Release Science Team.

Instrumentation

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

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

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

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

III.4 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.

WINE

The WINE collaboration, short for Warm Giant Planets in the TESS era, aims at validating and characterizing transiting warm giant planets of similar size as Jupiter, with orbital periods between 10 and 100 days, based on data from NASA's Transiting Exoplanet Survey Satellite (TESS) and using a network of precise photometric and spectroscopic facilities.

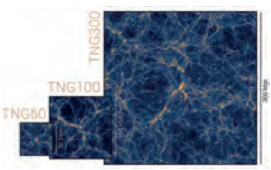
Gaia

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.

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.

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.

PRODIGE – PROtostars & DIsks: Global Evolution

PRODIGE is a large MPG-IRAM Observing Programme at the NOMEA interferometer on the Plateau de Bure in the French Alps, which is running from 2019 to 2023. The project aims to deliver the first coherent, statistically-significant study of the physics and chemistry of young protostellar 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.

EDEN

The ExoEarth Discovery and Exploration Network (EDEN) transit survey is a large-scale search for transiting habitable zone Earth-sized planets around nearby stars. In contrast to most ongoing and past surveys, the EDEN team utilizes large research telescopes (0.8 m–2.4 m), which allows for efficient probing of the habitable zones of late M-dwarf stars.

III.5 Highlights

One helium droplet at a time

Simulating nature's cosmic laboratory

Thomas Henning, Director at the Max Planck Institute for Astronomy and Sergiy Krasnokutskiy from the University of Jena have found an elegant new method to measure the energy of simple chemical reactions, under similar conditions as those encountered by atoms and molecules in the early solar system. Their method promises accurate measurements of reaction energies that can be used to understand chemical reactions under space conditions – including those reactions that were responsible of creating organic chemicals as the raw material for the development of life.

In order for life to form, nature needed plenty raw materials in the shape of complex organic molecules. Some of those molecules are likely to have formed long before, in space, during the birth of the Solar System. Systematic studies of the necessary chemical reactions, which take place on the craggy and convoluted surfaces of dust grains, were and are hampered by a lack of data. Which elementary reactions, involving which individual reactants are possible? What temperature is required for a reaction to take place? Which molecules are produced in those reactions? Thomas Henning, director at the Max Planck Institute for Astronomy (MPIA), and Sergiy Krasnokutskiy of the MPIA's Laboratory Astrophysics Group at the University of Jena have developed an elegant method to study such elementary surface reactions – using minute liquid helium droplets.

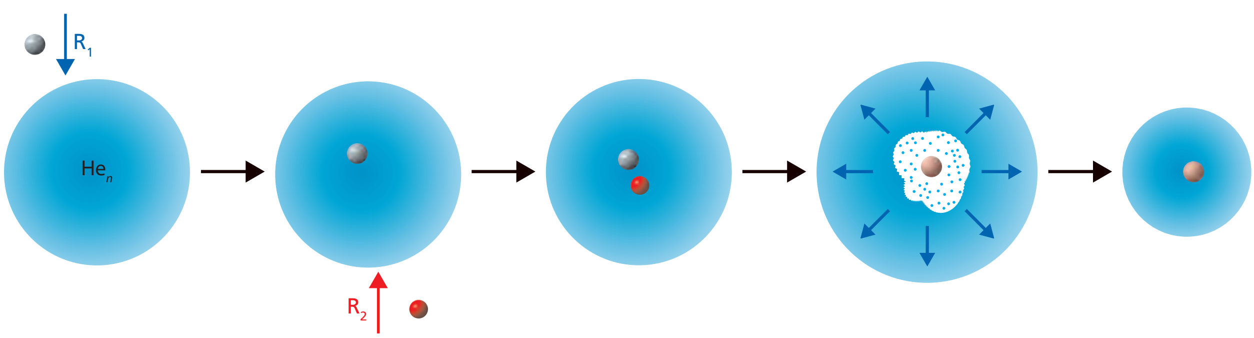
In the early solar system, long before the formation of Earth, complex chemical reactions took place, creating substantial amounts of organic molecules. The cosmic laboratory for these works of chemical synthesis was provided by grains of dust – clusters of mostly silicates and carbon, covered with a mantle of ice, with complicated and delicate tendrils and ramifications, and on this basis with one crucial property: A comparatively large surface on which chemical reactions could take place. In the millions of years that follows, many of those dust grains would cluster together to form ever larger structures, until finally, solid planets emerged, orbiting the young Sun.

Creating the raw ingredients for life

While all of the organic compounds synthesized on the grain surfaces would be destroyed by the unavoidable heat during planet formation, some of the molecules remained in waiting, encapsulated in, or clinging to the surface of, smallish grains or lumps of rock, as well as in the icy bodies of the comets. By one account of the history of life, once Earth's surface had cooled sufficiently for liquid water to form, it was these grains and rocks, hitting Earth's surface in the shape of meteorites, some of them landing in warm, small, ponds, that provided the chemical basis for life to form on our home planet.

In order to understand the early natural chemical experiments in our universe, we need to know the properties of the various reactions. For instance, do certain reactions need a specific activation energy to happen? What is the eventual product of a given reaction? Those parameters determine which reactions can occur under what conditions in the early Solar System, and they are key for any realistic reconstruction of early solar system chemistry.

Fig. III.5.1: Schematic representation of the new method: Two reactants R1 and R2 are added to a helium droplet. The energy released in the resulting reaction decreases the droplet's size. The decrease in size can be measured, and allows researchers to deduct the reaction energy.



Credit: S. Krasnokutskiy / MPIA

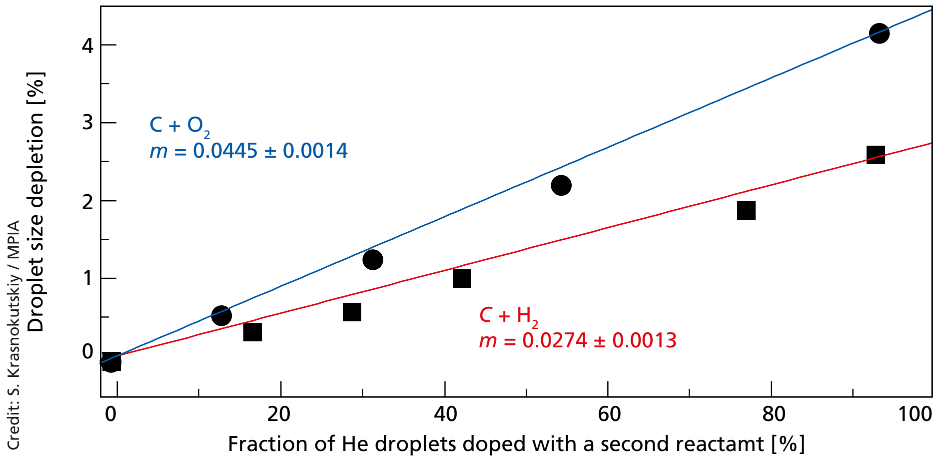


Fig. III.5.2: The graph shows the measured depletion of the He droplet beam caused by exothermic chemical reactions between a carbon atom (C) and a second reactant, either hydrogen (H_2) or oxygen (O_2). Depending on how many droplets are doped with a second reactant, the overall depletion rises linearly indicating heat dissipation.

Scarce data about low-temperature surface reactions

Yet precise data on these reactions is surprisingly scarce. Instead, a substantial part of chemical research is dedicated to the study of such reactions in the gaseous phase, with the atoms and molecules floating freely, colliding, and forming compounds. But the crucial chemical reactions in space needed to build up larger organic molecules take place under markedly different conditions – on the surfaces of dust grains. This changes even the basic physics of the situation: When a new molecule is formed, the energy of the chemical bond formation is stored in the newly created molecule. If this energy is not passed on to the environment, the new molecule will quickly be destroyed. This prevents the formation of many species of molecules in the gas phase. On a surface, or in a medium, where energy can readily be absorbed by the additional matter present, the conditions for certain types of reactions building complex molecules, step by step, are much more favorable.

Henning and Krasnokutskiy developed an elegant method for measuring the energetics of such reactions. Their mock-ups of cosmic laboratories are miniature helium droplets, a few nanometers in size, drifting in a high vacuum (see Fig. III.5.1). The reactants – that is, the atoms or molecules meant to take part in the reaction – are brought into the vacuum chamber as gases, but in such minute amounts that helium droplets are overwhelmingly likely to pick up either a single molecule of each required species or none, but not more. The helium droplets act as a medium that, similar to the surface of a dust grain, can absorb reaction energy, allowing reactions to happen under similar conditions to those in the early Solar System. This reproduces a key feature of the relevant surface chemistry (although other properties, such as catalytic properties of a specific dust surface, are not modelled).

Nanodrops as measuring devices

Furthermore, the two astronomers used the helium nanodrops as energy measuring devices (calorimeters). As reaction energy is released into the drop, some of the Helium atoms will evaporate in a predictable fashion. The remaining drop is now smaller than before – a difference in size that can be measured using two alternative methods: an electron beam (a larger drop is easier to hit than a smaller one!) or a precise measurement of the pressure in the vacuum chamber created by Helium droplets hitting the wall, where larger droplets produce greater pressure. Figure III.5.2 depicts the measurements in terms of He droplet mass loss (depletion) caused by the chemical reactions versus the number of droplets doped with two reactants, which corresponds to the number of reactions in the chamber. As a result, the linear slope of the correlation is a measure of the heat released by the reaction.

By calibrating their method using reactions that had been studied in detail beforehand, and whose properties are well-known, the two astronomers were able to increase the method's accuracy considerably. All in all, the new method provides an elegant new way of investigating the formation pathway of complex organic molecules in space. This should enable researchers to be more specific about the raw materials nature had to work with in the run-up of the emergence of life on Earth. But there is more:

The first measurements using the new technique confirm a trend that had already been visible in other recent experiments: On surfaces, at low temperatures, carbon atoms are surprisingly reactive. The researchers found a surprisingly high number – almost a dozen – of reactions involving carbon atoms which are barrierless, that is, which do not require extra energy input to proceed, and hence can occur at very low temperatures. Evidently, the condensation of atomic gas at low temperatures is bound to lead to the formation of a large variety of organic molecules. But that large possible variety also means that molecules of each specific species will be very rare.

This, in turn, suggests that astronomers might be drastically underestimating the amount of organic molecules in outer space. When it comes to estimating abundances, astronomical observations examine the trace signatures (spectral lines) of each molecular species separately. If there are many different species of organic molecules out there, each separate species can "fly under the radar." Its molecules might be present only in amounts too little for astronomers to detect, and in addition, even the tell-tale signatures of the molecules (more generally those of specific functional groups common to different types of molecules) could be slightly altered, making the molecule evade detection. But added up, it is possible that all these separate species of molecule together could make up a substantial amount of matter in outer space – a hidden outer-space world of organic chemistry.

Thomas K. Henning

in collaboration with
Sergiy A. Krasnokutskiy (Laboratory Astrophysics Group of the Max Planck Institute for Astronomy, Friedrich Schiller University, Jena, Germany)

Thomas K. Henning and Sergiy Krasnokutskiy 2019, "Experimental characterization of the energetics of low-temperature surface reactions" in Nature Astronomy, Vol. 3, 568. DOI: 10.1038/s41550-019-0729-8

III.6 Highlights

Exoplanet under the looking glass

New method allows precise determination of exoplanet's spectra and position

For the first time, astronomers have succeeded in investigating an exoplanet using optical interferometry. The new method allowed them to measure the position of the exoplanet HR 8799e with unprecedented accuracy. Also, the planet's spectrum was recorded as precisely as never before, paving the way for future searches for life on other planets. The measurements, which were obtained with the participation of astronomers from the Max Planck Institutes for Astronomy and for Extraterrestrial Physics, were performed with the GRAVITY instrument at ESO's Paranal Observatory.

Investigating exoplanets in detail and without confounding noise is difficult. In general, with increasing distance, it becomes more and more difficult to image fine details of an astronomical object. Furthermore, exoplanets are typically buried in the glare of their much brighter host stars. A group of researchers led by Sylvestre Lacour of the Observatoire de Paris and the Max Planck Institute for Extraterrestrial Physics, also including MPIA astronomers, has been able to demonstrate a new method of investigation that mitigates these problems and thereby provides a new perspective on exoplanets.

Key to the new technique is the GRAVITY instrument, which has been in operation at the European Southern Observatory's Very Large Telescope Interferometer (VLTI) at Paranal Observatory in Chile since 2016. Using a technique known as interferometry, which exploits the wave nature of light, GRAVITY is able to combine the light of several telescopes to form a common image. Combined, the four 8-metre-telescopes of the Very Large Telescope (VLT) can make images so detailed that a single telescope would need to have a mirror diameter of approximately 100 meters to provide the same level of detail.

The study of the exoplanet HR 8799e that has now been published is the first to demonstrate the potential of interferometric observations for the investigation of exoplanets in practice. The planet is one of only a few (about 120 out of 4000) for which direct images exist; so far, most exoplanets have only been detected indirectly. HR 8977e is part of a young five-body-system, a mere 130 light-years away from us, which consists of the star HR 8799 and four planets (as far as we know, at least). All of the planets are gas giants with between 5 and 10 times the mass of Jupiter.

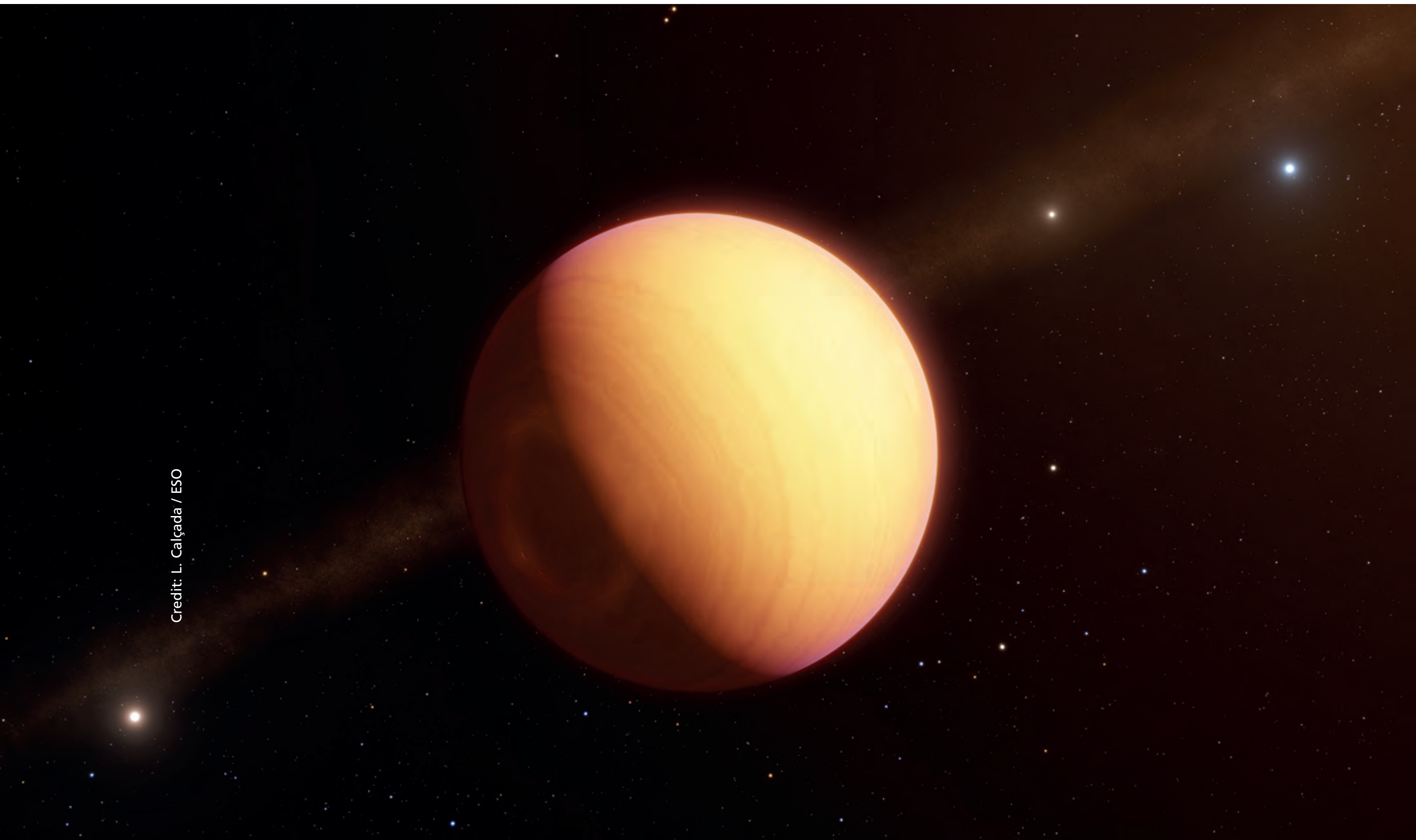


Fig. III.6.1: Alien world: Exoplanet HR 8799 e has been analyzed spectroscopically separate from the parent star HR 8799 using the new technique (artistic impression).

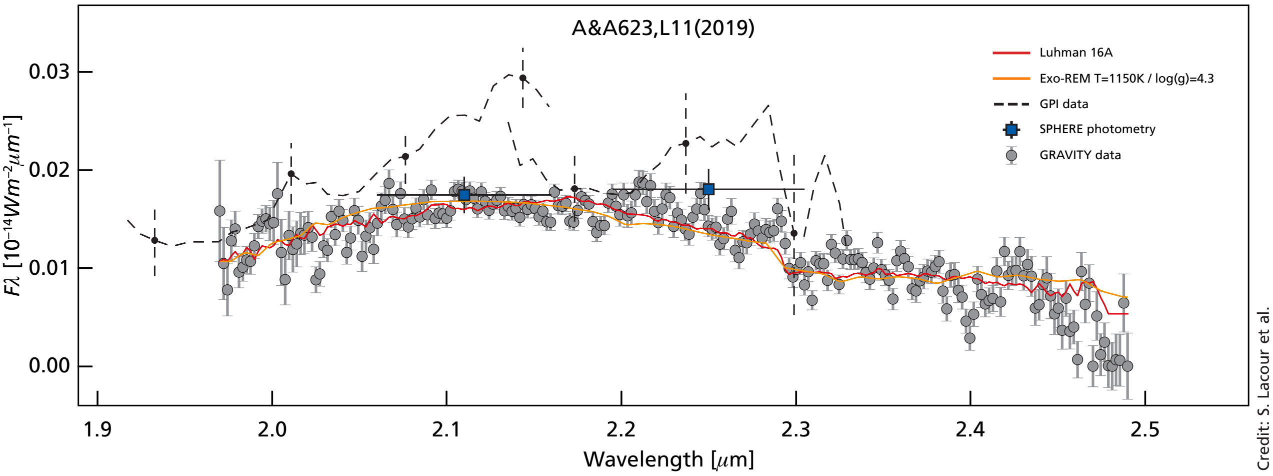


Fig. III.6.2: GRAVITY spectrum of HR 8799 e when compared to archival observations with the GPI and SPHERE instrument. The increased quality of the spectra when using GRAVITY is evident from this plot. The spectrum is shown in comparison with Exo-REM models (Charnay et al. 2018) and a spectrum of the benchmark brown dwarf Luhman 16A.

Among the four, HR 8799e is the one closest to the host star. That is why it is particularly difficult to clearly distinguish light from the star and light from the planet in observations. The star's radiation is about 20 000 times more intense than that of the exoplanet – under normal circumstances, the star drowns out the planet's light. Since HR 8799e is so close to its host star, the effect is particularly large.

GRAVITY was able to deliver much more detailed images of the exoplanet than its predecessor instruments. With the help of these high-resolution images, the astronomers were able to calculate the distance between the star and the planet ten times more accurately than before. This allows a more precise determination of the planet's orbit, which, according to the new measurements, appears to be slightly inclined relative to the orbital plane of the other planets of the HR 8799 system.

Interferometry is a particularly powerful way to distinguish between the light of the planet and the light of the star – the separation of the two is much cleaner than with conventional methods of blocking out the star's light using a mask ("coronagraphy"). With this clean separation, the astronomers were able to measure the spectrum of HR 8799e much more accurately than before. Benjamin Charnay (Paris Observatory) and Paul Molliere (MPIA) provided sophisticated atmospheric modelling using these spectra, which is crucial for better characterizing the astrophysical properties like temperature and chemical composition.

From this they deduced that the atmosphere of the relatively young gas planet, which is 30 million years old, has a temperature of respectable 880 degree Celsius. But the spectrum also had a surprise in store. Going by the planets of our own solar system, one would expect large amounts of methane in the atmosphere of a gas planet this hot. But the atmosphere of HR 8799e hardly contains any methane at all. Instead, the researchers found major amounts of carbon monoxide. This shows that the chemical conditions in hot young planets such as HR 8799e are markedly different from the Solar System gas giants – and at the same time, it underlines the key role of atmospheric spectroscopy for learning about exoplanets.

Currently, the astronomers are planning long-term follow-up observations with GRAVITY. With this additional data, they should be able to reconstruct the orbit of HR 8799e with such great accuracy that there would be another first: the first time where the motion within a spatially resolved exoplanet system would reveal not only the gravitational influence of the central star, but also the mutual attraction of the gas planets. Such observations should allow for an accurate estimate of the masses of the four gas planets. To the best of our current knowledge, HR 8799e needs between 40 and 50 years for one complete orbit.

The new observations are also of interest for future searches for traces of life in the universe. The main current search strategy aims to detecting tell-tale signs of life in the spectrum of an exoplanet's atmosphere. The successful GRAVITY observation opens up a way for taking spectra of this kind with greater accuracy.

Wolfgang Brandner, Paul Molliere, Silvia Scheithauer

in collaboration with

Sylvestre Lacour, Benjamin Charnay (Paris Observatory), Anne-Lise Maire (University of Liege)

GRAVITY Collaboration et al. 2019, "First direct detection of an exoplanet by optical interferometry" in Astronomy & Astrophysics, 623, L11. DOI: 10.1051/0004-6361/201935253

III.7 Highlights

Galactic conveyor belts feed star formation

How magnetic fields push the formation of stars

The role of magnetic fields in the formation of stars has been a hot topic among astrophysicists for decades. Juan Diego Soler has shown that magnetic fields can favour and advance the compression of interstellar matter – a prerequisite for the formation of stars. This conclusion is based on the finding that in star-forming regions the interstellar matter, depending on its density, is sometimes oriented parallel to, sometimes rather perpendicular to, the magnetic field lines.

Stars form from compressed clouds of the Interstellar Medium (ISM). The ISM consists of gas (mostly hydrogen) and tiny particles of carbon and silicates, which the astrophysicist calls dust. If the ISM reaches a sufficiently high density, the self-gravity leads to a collapse of the initially cold matter down to hot stars. How such clouds form and condense, however, is not yet fully understood. For 60 years, we have known that magnetic fields are a major component of ISM in the Milky Way and other galaxies. They contribute significantly to the total pressure, which balances the ISM against gravity. Still, their exact role in the process of star formation is the subject of lively discussions.

To approach this puzzle, Juan Diego Soler of the Max Planck Institute for Astronomy (MPIA) investigated the orientation of magnetic fields concerning the density distribution towards the most nearby regions of star formation at distances of up to 450 parsecs from the Sun. If the magnetic field has a strong influence on the ISM, it should shape the ISM's density structures.

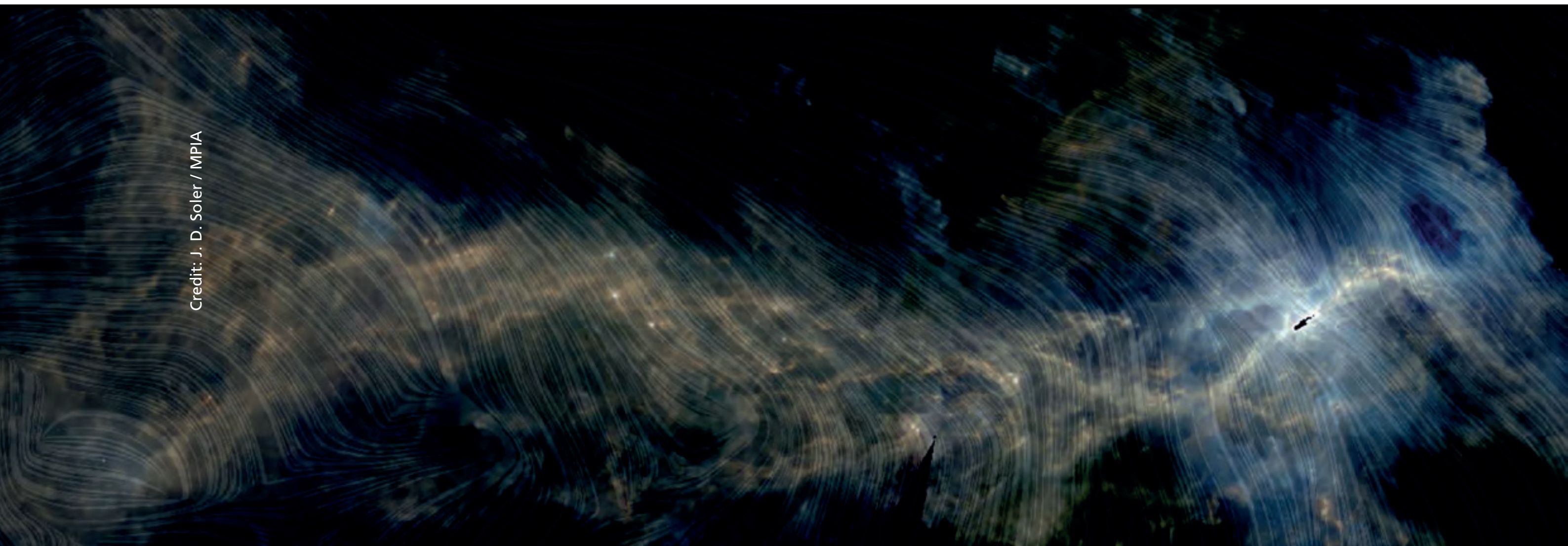
In fact, in all cases, he found a parallel alignment of the magnetic fields to the diffuse, i.e. less dense, component of the ISM. However, at higher densities of the ISM, there was a gradual shift in alignment towards larger angles. In the densest zones, the magnetic field was even perpendicular to the structures of the ISM. This finding is shown in Figure III.7.1.

The magnetic field guides the ISM

These results confirm a scenario illustrated in Figure III.7.2. The partially ionised, diffuse ISM is coupled to the magnetic field via electromagnetism and can only move along the field lines (a). Charged particles that move in a magnetic field experience a sideways force. It is proportional to the strength of the magnetic field, the component of the velocity perpendicular to the magnetic field, and the charge of the particle. This force is known as the Lorentz force. Collisions with the electrically neutral components, such as the dust, carry them along. Therefore, the less dense zones appear to be aligned with the magnetic field. The turbulence in the clouds helps them to expand along the field lines into filaments.

When triggered by external influences, such as expanding bubbles from supernovae explosions or the passage of the matter through a spiral arm, different clouds move towards each other as if on conveyor belts. When they converge, they continuously form an accumulation of ISM, which then has a preferred direction rather perpendicular to the magnetic field lines (b). The conveyor belt transports additional ISM and increases the density until it becomes so high that the cloud (or parts of it) collapses under its gravity (c). During this phase, the magnetic field is not strong enough to prevent collapse. The field retains its orientation with respect to the density profile during the collapse, which in turn distorts the magnetic field.

Fig. III.7.1: Infrared light and magnetic field lines toward the Orion A cloud, revealed by the Herschel and Planck space observatories. With enough gas to form tens of thousands of stars like the Sun, this is the most nearby site of high-mass star formation. The colours indicate the light emitted by interstellar dust grains. The grey bands show the orientation of the magnetic field.



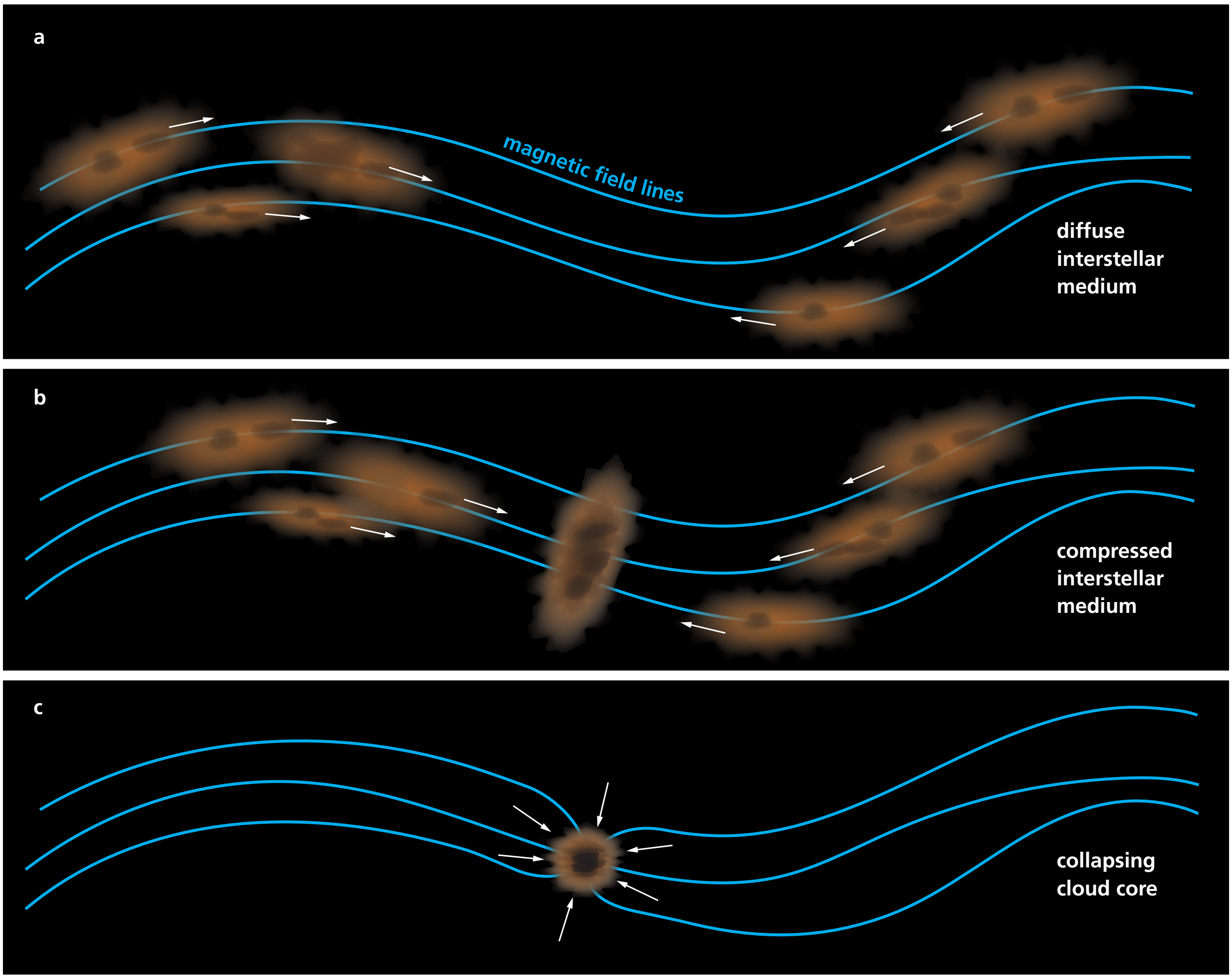


Fig. III.7.2: Illustration of the interplay between magnetic fields and the interstellar medium.

ESA space telescopes make the difference

Soler has been investigating the relationship between magnetic fields and the structure of star formation regions for several years. This time he used data from the Planck all-sky observations and the "Herschel Gould Belt Survey" (HGBS) project for his analysis. Both Herschel and Planck went into service in mid-2009. They measured the radiation of the cold ISM at different wavelengths.

The Herschel data are particularly suitable for determining the density distribution of the ISM from the radiation emitted with high spatial resolution. From the Planck data, Soler measured the polarisation of the radiation, which provides information about the magnetic field. The elongated dust particles of the ISM align themselves with the magnetic field and therefore function similarly to antennas. The planes of oscillation of the electric and magnetic fields of the emitted radiation thus have preferred directions, i.e. it is polarised. Astronomers have known for decades that the ISM emits partially polarised radiation. However, they have not yet been able to quantify the large-scale orientation to the structures in the ISM.

Image recognition techniques help to investigate ISM structures

Soler adapted a technique that is used, in a modified form, for image recognition – for example, in internet image searches or when creating panoramic images. It is based on the mathematical treatment of gradients, i.e. the strength and direction of changes, e.g. in the brightness of the images. Figure III.7.3 shows how patterns in the two images are identified by equal brightness gradients. The gradients used in the Planck and Herschel data relate to the magnetic field and density distribution of the ISM. Thus, Soler was able to calculate with statistical methods under which conditions both components are rather parallel or perpendicular to each other.

All in all, the Planck satellite polarisation observations have revealed unprecedented details on the interstellar magnetic fields. They promise to be the cornerstone for a better understanding of the magnetised ISM in the future, which will be improved with forthcoming satellite and balloon-borne missions.

Juan Diego Soler

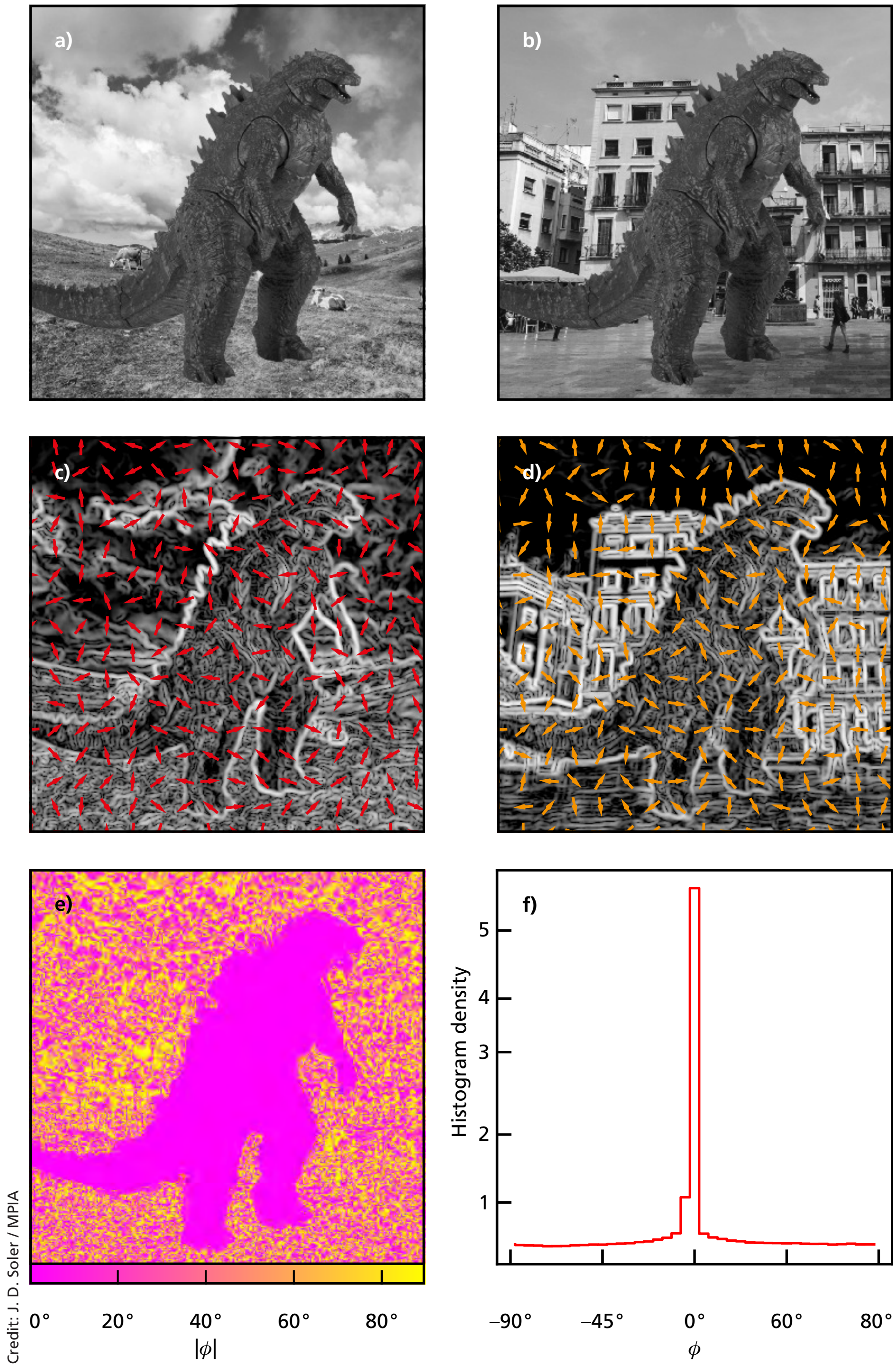


Fig. III.7.3: Illustration of the method of the histogram of relative orientations (HRO). A pair of images *(a and b)* is characterised by the slope and the direction of their brightness variations, called gradients *(c and d)*. The distribution of the relative orientation angles makes the corresponding areas visible in which the gradients of the two images coincide *(e)*, i.e. the angle difference there is 0°. The histogram of the relative orientations *(f)* summarises the frequencies of the individual pairwise angle differences. The number of angles around 0° corresponds to the agreement of the orientations in both images.

Juan D. Soler 2019, "Using Herschel and Planck observations to delineate the role of magnetic fields in molecular cloud structure" in Astronomy & Astrophysics, 629, A96. DOI: 10.1051/0004-6361/201935779

III.8 Highlights

For new-born planets, solar systems are naturally baby-proof

Numerical simulations by a group of astronomers, led by Mario Flock, have shown that young planetary systems are naturally "baby-proof": Physical mechanisms combine to keep young planets in the inner regions from taking a fatal plunge into the star. Similar processes also allow planets to be born close to stars – from pebbles trapped in a region close to the star. The research explains findings made by the Kepler space telescope that show a large number of super-Earths orbiting their stars very closely, at the edge of the baby-proof region.

When a child is born, parents will make sure they have baby-proofed their home, setting up safety barriers which keep the child away from particularly dangerous areas. New research on the formation of planets show that something very similar happens in young planetary systems.

Planets form around a young star, which is surrounded by a disk of gas and dust. Inside this protoplanetary disk, dust grains stick together, growing larger and larger. After a few million years, they have reached a few kilometres in diameter. At that point, gravity is strong enough to pull such objects together to form planets, round objects, solid or with a solid core, with diameters of a few thousand kilometres or more.

A curious crowding at the inner boundary

Just like toddlers, solid objects in such a young planetary system tend to move in all directions – not only orbiting around the star, but drifting inwards or outwards. This can become potentially fatal for planets that are already relatively close to the central star.

Near the star, we will only encounter rocky planets, with solid surfaces, similar to our Earth. Planetary cores can only capture and keep significant amounts of gas to

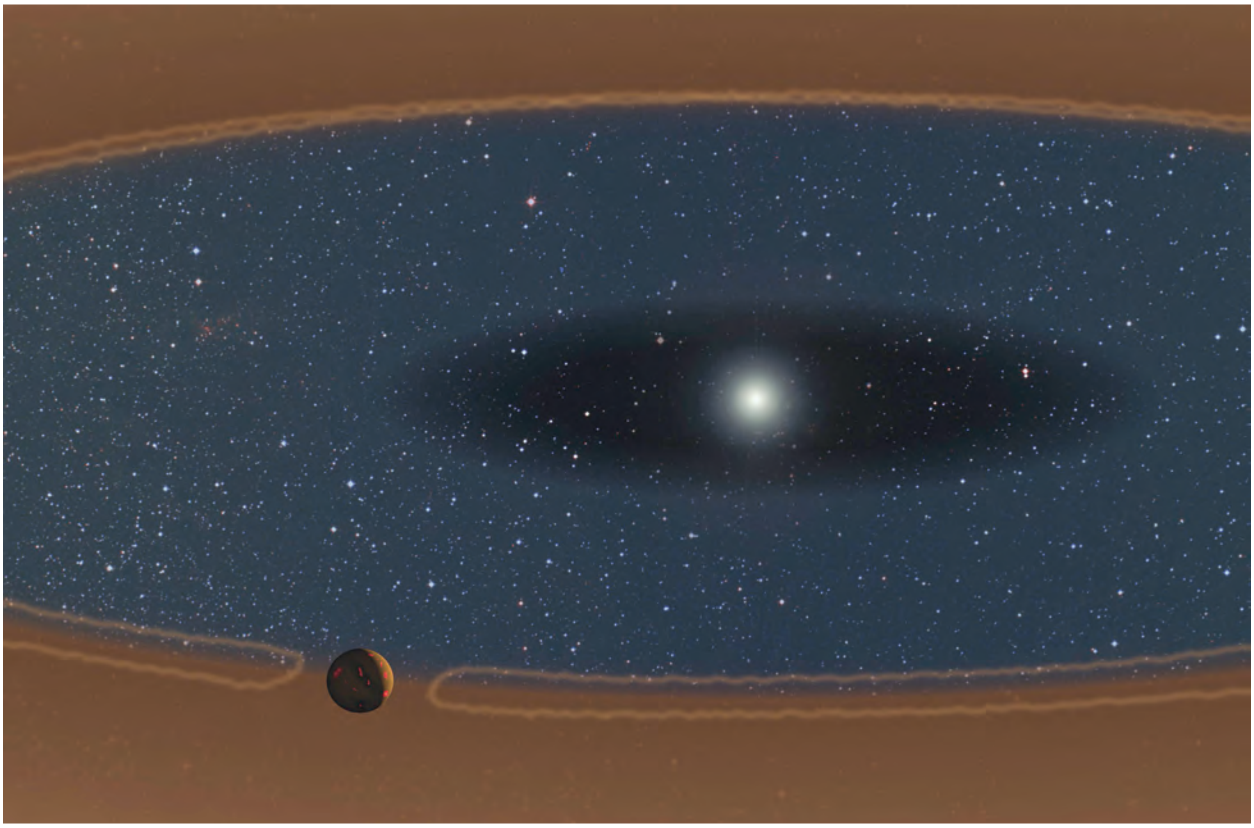


Fig. III.8.1: Young planet in a baby-proof system: the new results shows how a boundary within the disk around a young, Sun-like star acts as a barrier that keeps planets from falling into the star.

Credit: MPIA graphics department

become gas giants much further out, away from the hot star. But the simplest kind of calculation for the motion of a planet near the star, in the gas of a protoplanetary disk, shows that such a planet should continually drift inwards, plunging into the star on a time scale of less than a million years, much shorter than the lifetime of the disk.

If this were the whole picture, it would be puzzling that NASA's Kepler satellite, examining stars similar to the Sun (spectral types F, G and K), found something completely different: numerous stars have very closely orbiting so-called super-Earths, rocky planets that are more massive than our own Earth. Particularly common are planets with periods around 12 days, going down to periods as low as 10 days. For our Sun, that would correspond to orbital radii around 0.1 astronomical units, only about one quarter of the orbital radius of Mercury, the planet closest to our Sun in our own Solar System.

This was the puzzle that Mario Flock, a group leader at the Max Planck Institute for Astronomy, set out to solve, together with colleagues from the Jet Propulsion Laboratory, the University of Chicago and Queen Mary University, London. The researchers involved are experts in simulating the complex environment in which planets are born, modelling the flows and interactions of gas, dust, magnetic fields, and of planets and their various precursor stages. Faced with the apparent paradox of the close-orbit Kepler super-Earths, they set out to simulate planet formation close to Sun-like stars in detail.

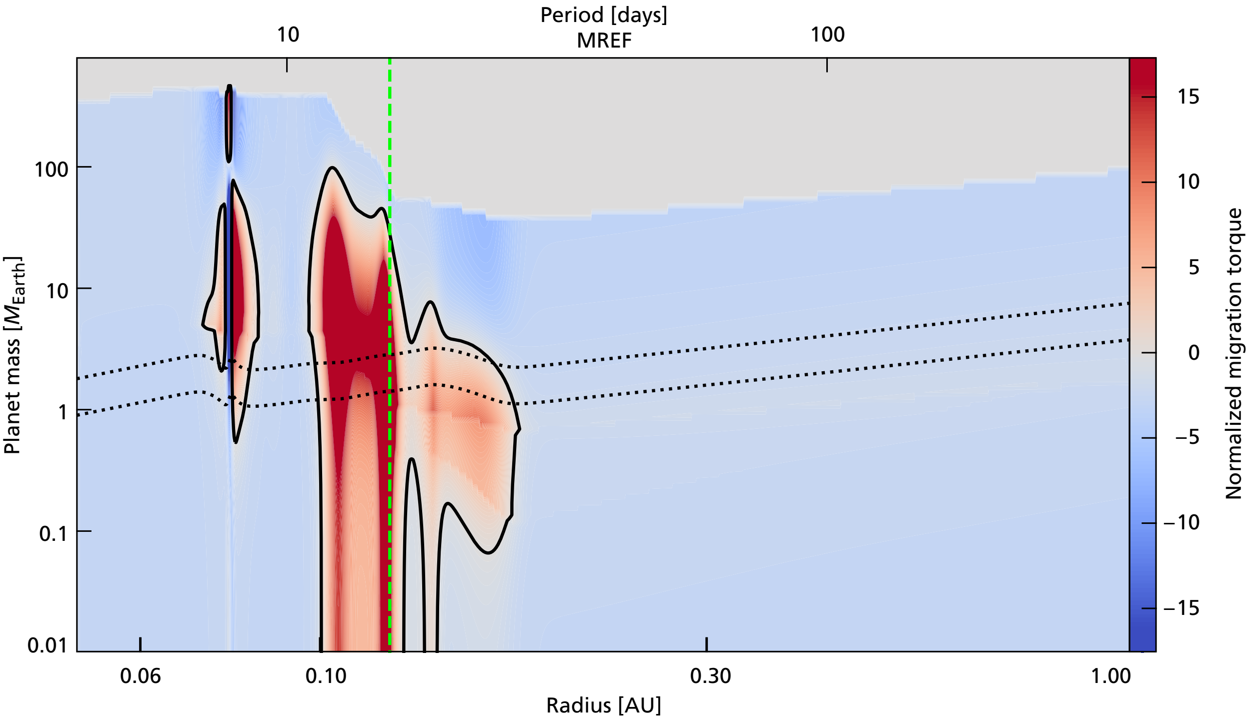
Solar-System-scale baby-proofing

Their results were unequivocal, and suggest two possible reasons behind the common occurrence of closely-orbiting planets. The first is that, at least for rocky planets with masses of up to 10 times the mass of the Earth ("super-Earths" or "mini-Neptunes"), those early star systems are baby-proof.

The safety barrier keeping young planets out of the danger zone works as follows. The closer we get to the star, the more intense the star's radiation. Inside the boundary called the silicate sublimation front, the disk temperature rises above 1200 K, and dust particles (silicates) will turn to gas. The extremely hot gas inside that region becomes very turbulent. This turbulence transports the gas towards the star at high speed, thinning out the inner region of the disk in the process.

As a young super-Earth travels through the gas, it is typically accompanied by gas co-rotating with the planet on an orbital path similar to a horseshoe. As the planet drifts inward and reaches the silicate sublimation front, the gas particles moving from the hot thinner gas to the denser gas outside the boundary give the planet a small kick. In this situation, the gas will exert an influence (in physics terms: a torque) on the travelling planet,

Fig. III.8.2: The diagram illustrates migration and pebble accumulation zones inside the inner 1 au of a young solar type star that is still accreting material from the surrounding disk. Inward (blue areas) and outward (red areas) migration depends on the planetary mass. The black solid lines that separate these areas indicate the locations where planetary migration stops. The location of the pebble trap is depicted by the vertical green dashed line.



Credit: M. Flock et al. / MPIA

and crucially, due to the jump in density, that influence will draw the planet away from the boundary, radially outward. In this way, the boundary serves as a safety barrier, keeping the young planets from plunging into the star. And the location of the boundary for a Sun-like star, as predicted by the simulation, corresponds to the lower limit for orbital periods found by Kepler. So why are there so many super-Earths in close orbit, as the Kepler telescope has shown? Evidently because young planetary systems have a built-in baby-proof barrier of sorts.

Planet-building at the boundary

There is an alternative possibility: In tracing the movement of pebble-like, smaller objects a few millimetres or centimetres in size, the researchers found that such pebbles tend to collect closely behind the silicate sublimation front. In order for pressure to balance directly at the border, the thin gas in the transition region needs to rotate faster than usual (since there must be a balance between pressure and centrifugal force). This gas rotation is faster than the "Keplerian" orbital speed of an isolated particle orbiting the star on its own. A pebble that enters this transition region is forced into this faster-than-Keplerian motion, and immediately ejected again as the corresponding centrifugal forces push it outwards, like a small child sliding off the platform of a merry-go-round. This, too contributes to the frequency of closely orbiting super-Earths. Not only do previously formed super-Earths collect at a baby-proof barrier. The fact that pebbles collect at that barrier as well provides ideal conditions for super-Earths newly forming at that location!

The results did not come as a complete surprise for the researchers. In fact, they had found a similar pebble trap in models of much heavier stars ("Herbig stars"), although at a much greater distance from the star. The new results extend this to Sun-like stars, and they add the baby-proofing mechanism for new-born planets. Furthermore, the new article is the first that provides a comparison with statistical data from the Kepler space telescope, carefully taking into account that Kepler will only be able to see certain kinds of systems (notably where we see the orbital plane nearly edge-on).

What about our own Solar System?

Interestingly, by these criteria, our own Solar System could also have harboured an Earth-like planet closer to the Sun than the current innermost planet, Mercury. Is the fact that there is no such planet a statistical fluke, or did such a planet exist and was ejected from the Solar System at some time? That is one interesting question for additional research. As Mario Flock says: "Not only that our Solar System was baby-proof – it is possible that the baby thus protected has since 'flown the nest'!".

Mario Flock

in collaboration with

Neal Turner (JPL/CalTech, Pasadena, USA),
Gijs Mulders (Department of the Geophysical Sciences, The University of Chicago, USA)

Mario Flock et al. 2019, "Planet formation and migration near the silicate sublimation front in protoplanetary disks" in Astronomy & Astrophysics, 630, A147. DOI: 10.1051/0004-6361/201935806

III.9 Highlights

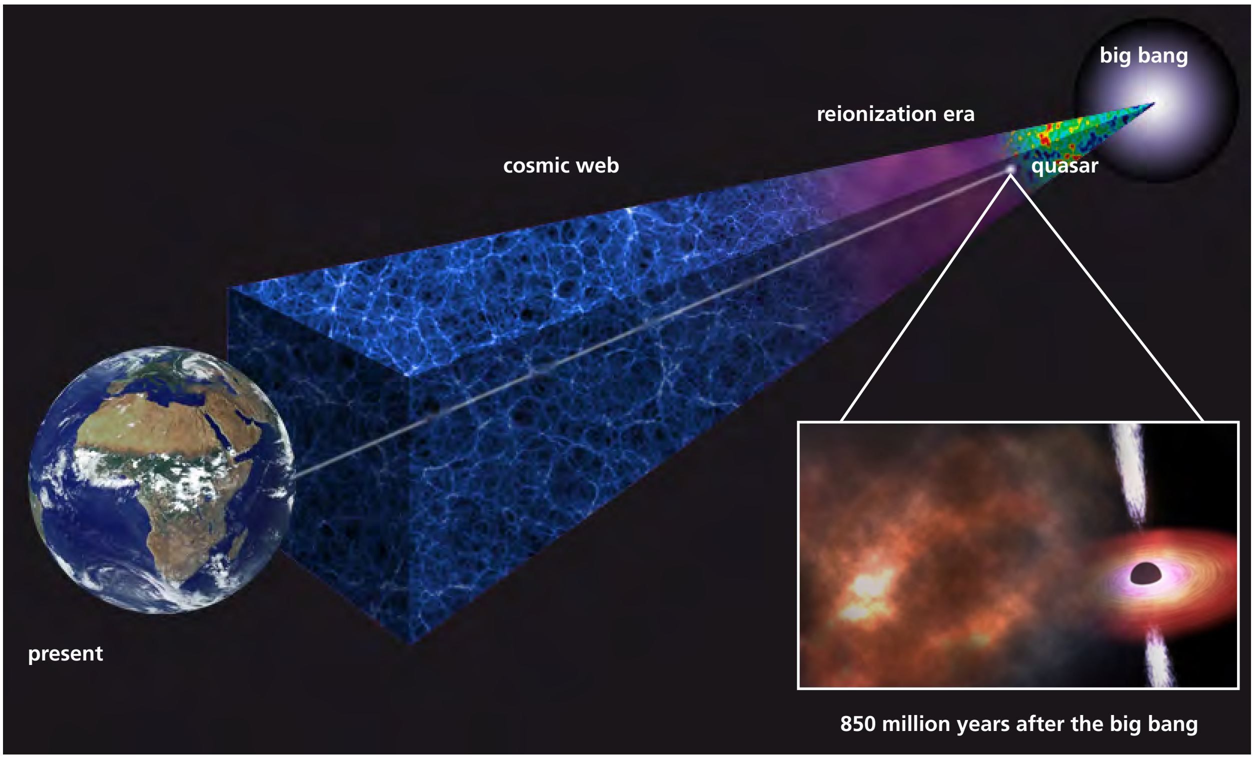
Ancient gas cloud shows that the first stars must have formed very quickly

Astronomers led by Eduardo Bañados have discovered a gas cloud that contains information about an early phase of galaxy and star formation, merely 850 million years after the Big Bang. The cloud was found serendipitously during observations of a distant quasar, and it has the properties that astronomers expect from the precursors of modern-day dwarf galaxies. When it comes to relative abundances, the cloud's chemistry is surprisingly modern, showing that the first stars in the Universe must have formed very quickly after the Big Bang.

When astronomers look at distant objects, they necessarily look back in time. The gas cloud discovered by Eduardo Bañados and his collaborators is so distant that its light has taken nearly 13 billion years to reach us; conversely, this light tells us how the gas cloud appeared nearly 13 billion years ago, no more than about 850 million years after the Big Bang. For astronomers, this is an extremely interesting epoch. Within the first several hundred million years after the Big Bang, the first stars and galaxies formed, but the details of that complex evolution are still largely unknown.

This very distant gas cloud was a fortuitous discovery. Bañados, then at the Carnegie Institution for Science, and his colleagues were following up on several quasars from a survey of 15 of the most distant quasars known ($z \leq 6.5$), which had been prepared by Chiara Mazzucchelli as part of her PhD research at the Max Planck Institute for Astronomy. At first, the researchers just noted that the quasar P183+05 had a rather unusual spectrum, that is, the rainbow-like decomposition of the quasar's light into the different wavelength regions. But when Bañados analyzed a more detailed spectrum,

Fig. III.9.1: Astronomers found a pristine gas cloud in the proximity of one of the most distant quasars known, seen just 850 million after the Big Bang (1/14th of the Universe's current age). The gas cloud absorbs some of the light from the background quasar, leaving signatures that allow astronomers to study its chemical composition. This is the most distant gas cloud for which astronomers have been able to measure a metallicity to date. This system has one of the smallest amounts of metals ever identified in a gas cloud but the ratios of its chemical elements are still similar to what observed in more evolved systems.



Credit: MPIA graphics department

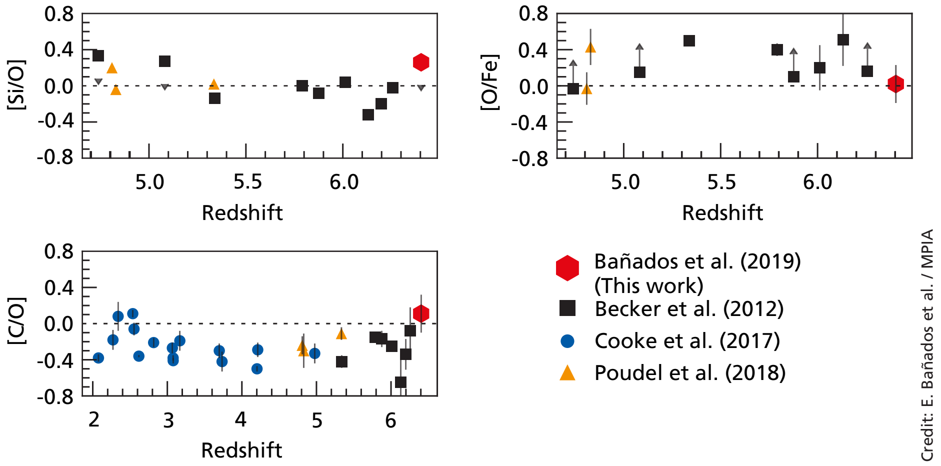


Fig. III.9.2: Relative abundances of chemical elements identified in clouds enveloping host galaxies at varying redshift. A red hexagon represents the values of the cloud featured in this report. This demonstrates that its relative chemical abundances are surprisingly similar to the solar mix of elements.

obtained with the Magellan Telescopes at Las Campanas Observatory in Chile, he recognized that there was something else going on: The weird spectral features were the traces of a gas cloud that was very close to the distant quasar – one of the most distant gas clouds astronomers have yet been able to identify.

Lit up by a distant quasar

Quasars are the extremely bright active nuclei of distant galaxies. The driving force behind their luminosity is the galaxy's central supermassive black hole. Matter swirling around that black hole (before falling in) heats up to temperatures reaching hundreds of thousands of degrees, giving off enormous amounts of radiation. This allows astronomers to use quasars as background sources to detect hydrogen and other chemical elements in absorption: If a gas cloud is directly between the observer and a distant quasar, some of the quasar's light will be absorbed.

Astronomers can detect this absorption by studying the quasar's spectrum. The absorption pattern contains information about the gas cloud's chemical composition, temperature, density and even about the cloud's distance from us (and from the quasar). Behind this is the fact that each chemical element has a "fingerprint" of spectral lines – narrow wavelength regions in which that element's atoms can emit or absorb light particularly well. The occurrence of a characteristic fingerprint reveals the presence and abundance of a specific chemical element.

Not quite the cloud they were looking for

From the spectrum of the gas cloud, the researchers could immediately tell the distance of the cloud, and that they were looking back into the first billion years of cosmic history. They also found traces of several chemical elements including carbon, oxygen, iron, and magnesium. However, the amount of these elements was tiny, about 1/800 times the abundance in the atmosphere of our Sun. Astronomers summarily call all elements heavier than helium "metals"; this measurement makes the gas cloud one of the most metal-poor (and distant) systems known in the Universe. In the present study, after the astronomers had convinced themselves that they were looking at virtually pristine gas only 850 million years after the Big Bang, they started wondering whether this system might still retain chemical signatures produced by the first generation of stars.

Finding these first generation, so-called, "Population III" stars is one of the most important goals in reconstructing the history of the Universe. In the later epochs of the Universe, chemical elements heavier than hydrogen play an important role in letting gas clouds collapse to form stars. But those chemical elements, notably carbon, are themselves produced in stars, and flung into space in supernova explosions. For the first stars, those chemical facilitators would simply not have been there, since directly after the Big Bang phase, there were only hydrogen and helium atoms. That is what makes the first stars fundamentally different from all later stars.

The analysis showed that the cloud's chemical makeup was not chemically primitive, but instead the relative abundances were surprisingly similar to the chemical abundances observed in today's intergalactic gas clouds. The ratios of the abundances of heavier elements were very close to the ratios in the modern Universe. The fact that this gas cloud in the very early Universe already contains metals with modern relative chemical abundances poses key challenges for the formation of the first generation of stars.

So many stars, so little time

This study implies that the formation of the first stars in this system must have begun much earlier: the chemical yields expected from the first stars had already been erased by the explosions of at least one more generation of stars. A particular time constraint comes from supernovae of type Ia, cosmic explosions that would be required to produce metals with the observed relative abundances. Such supernovae typically need about 1 billion years to happen, which puts a serious constraint on any scenario of how the first stars formed.

Now that the astronomers have found this very early cloud, they are systematically looking for additional examples. As exciting as it is to measure metallicity and chemical abundances so early in the history of the Universe – it is very clear that, if they want to identify the signatures of the first stars, they will need to probe even earlier in cosmic history. The search is on for even more distant gas clouds, which could help astronomers understand how the first stars were born."

Eduardo Bañados Torres

in collaboration with

Michael Rauch (The Observatories of the Carnegie Institution for Science, USA)

Eduardo Bañados et al. 2019, "A Metal-poor Damped Lyα System at Redshift 6.4" in The Astrophysical Journal, Vol. 885, 59.
DOI: 10.3847/1538-4357/ab4129

III.10 Highlights

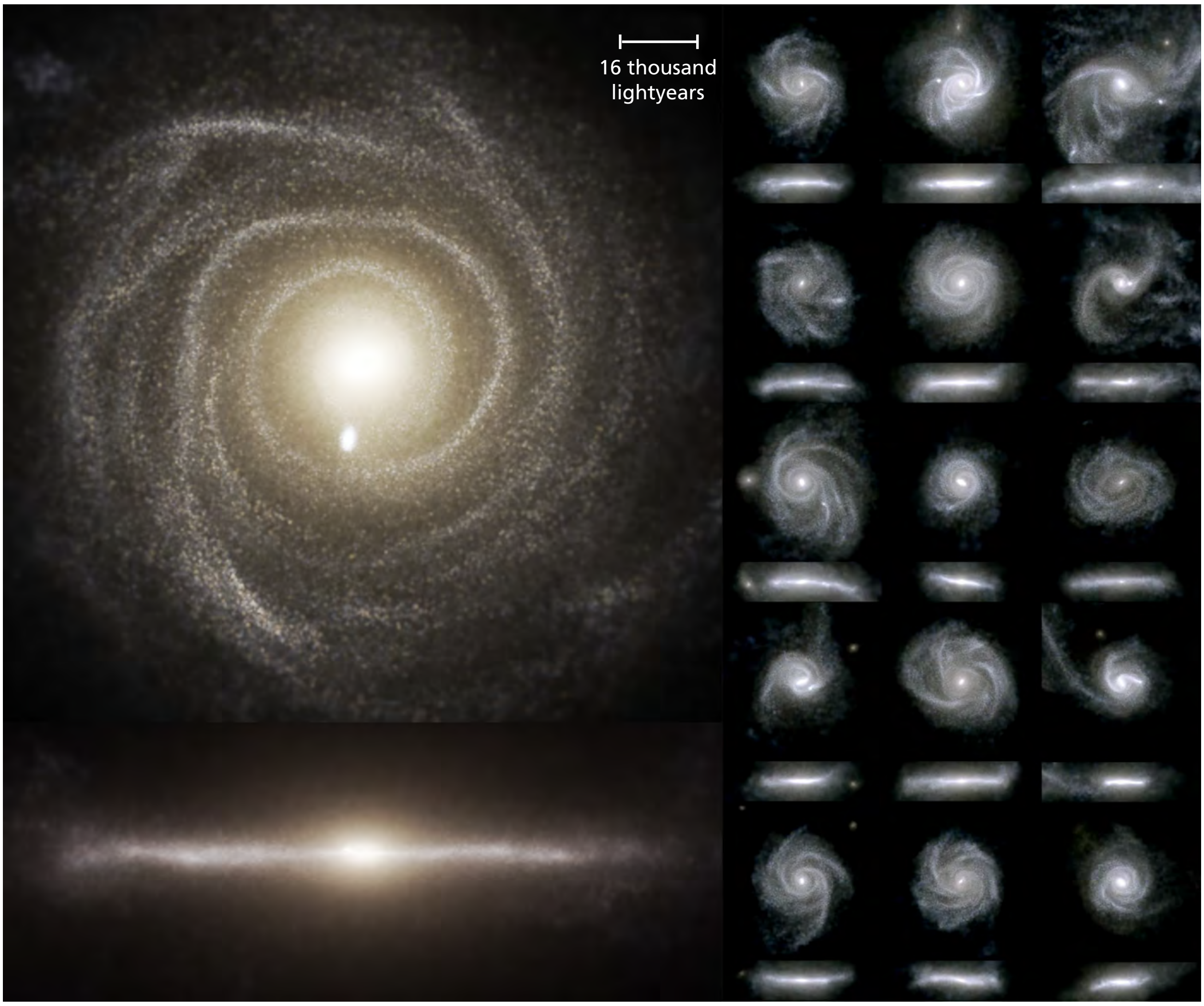
Galactic fountains and carousels

Order emerging from chaos

Scientists from Germany and the United States have unveiled the results of a newly-completed, state of the art simulation of the evolution of galaxies. TNG50 is the most detailed large-scale cosmological simulation yet. It allows researchers to study in detail how galaxies form, and how they have evolved since shortly after the Big Bang. For the first time, it reveals that the geometry of the cosmic gas flows around galaxies determines galaxy structure, and vice versa.

Astronomers running cosmological simulations face a fundamental trade-off: with finite computing power, typical simulations so far have been either very detailed or have spanned a large volume of virtual space, but not both. Detailed simulations with limited volumes can model no more than a few galaxies, making statistical deductions difficult. Large-volume simulations, in turn, typically lack fine details on smaller scales, which are important for describing individual galaxies. The TNG50 simulation, which has just been published, manages to avoid this trade-off. For the first time, it combines the idea of a large-scale cosmological simula-

Fig. III.10.1: Images of disk galaxies from the TNG50 simulation in visible light. For each galaxy, there is a face-on view (top) and an edge-on view. TNG50 has thrown new light on how disk galaxies like these form.



Credit: D. Nelson / MPA and the Illustris TNG team

Credit: D. Nelson / MPA and the Illustris TNG team

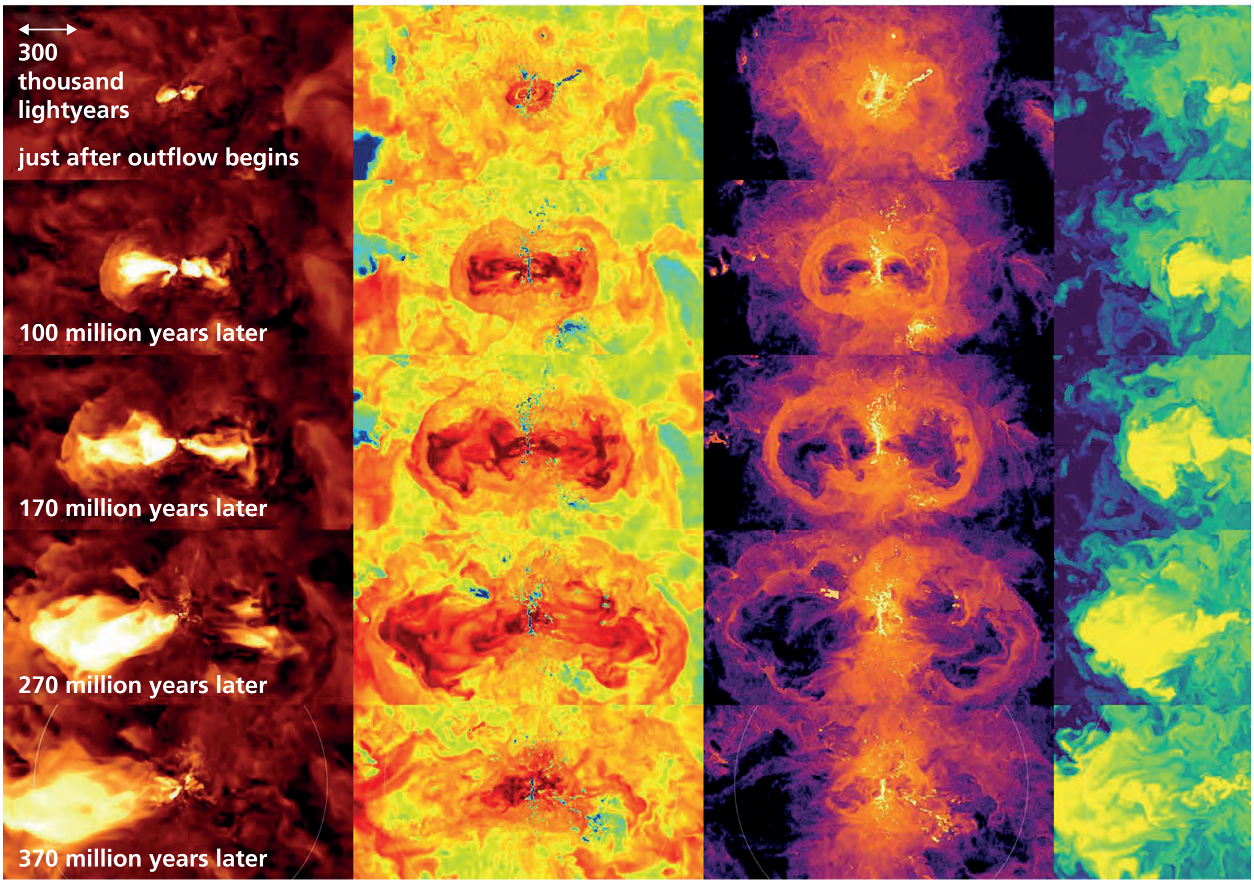


Fig. III.10.2: Outflow of gas from a galaxy. From top to bottom, each row represents a different snapshot, spanning 370 million years of cosmic evolution. The outflow is driven by energy set free near the active supermassive black hole in the galaxy's center. From left to right, the columns show false-color representations of the velocity, temperature, density and heavy element content within and around the galaxy. The galaxy itself is the cold (blue, second column from left) and dense (yellow, third column) disk of star-forming gas visible as a small, vertical structure in the center of each image.

tion – a universe in a box – with the computational resolution of "zoom" simulations, at a level of detail that had previously only been possible for studies of individual galaxies.

In a simulated cube of space that is more than 230 million light-years across, TNG50 can discern physical phenomena that occur on scales one million times smaller, tracing the simultaneous evolution of thousands of galaxies over 13.8 billion years of cosmic history. It does so with more than 20 billion particles representing dark matter, stars, cosmic gas, magnetic fields, and supermassive black holes. The calculation itself required 16,000 cores on the Hazel Hen supercomputer in Stuttgart working together, 24/7, for more than a year – the equivalent of fifteen thousand years on a single processor, making it one of the most demanding astrophysical computations to date.

Emerging phenomena in a simulated universe

The first scientific results from TNG50 published by a team led by MPIA's Annalisa Pillepich and Dylan Nelson (Max Planck Institute for Astrophysics, Garching), have revealed unforeseen physical phenomena. Numerical experiments of this kind are particularly successful when researchers get out more than they put in. In the TNG50 simulation, the researchers saw some interesting phenomena that had not been programmed explicitly into the simulation code: Phenomena that nevertheless emerged, in a natural fashion, from the complex interplay of the basic physics ingredients simulated in their model universe. TNG50 features two prominent examples for this kind of emergent behavior. The first concerns the formation of "disk" galaxies like our own Milky Way. Using TNG50 as a time machine to rewind the evolution of cosmic structure, researchers have seen how the well-ordered, rapidly rotating disk galaxies (which are common in our nearby universe) emerge from chaotic, disorganized, and highly turbulent clouds of gas at earlier epochs.

As the gas settles down, new-born stars are typically found on more and more circular orbits, eventually forming large spiral galaxies – galactic carousels. This shows that what has happened in our own Milky Way galaxy, with its comparatively thin disk, follows a cosmic trend: over the past 10 billion years, at least those galaxies that are still forming new stars have become more and more disk-like, and their chaotic internal motions have decreased considerably. The Universe is much less messy now than it was when it was just a few billion years old.

Interplay of gas flows and galaxies

As these galaxies flatten out, researchers found another emergent phenomenon, concerning high-speed outflows and winds of gas flowing out of galaxies. Such outflows and winds are launched as a result of supernovae explosions and supermassive black hole activity. Galactic gaseous outflows are initially also chaotic and flow away in all directions, but over time, they begin to become more focused along a path of least resistance. In the late universe, outflows are oriented within two conical volumes, emerging from the galaxy in opposite directions – like two ice cream cones placed tip to tip, with the galaxy swirling at the center.

These winds slow down as they attempt to leave the gravitational well of the dark matter halo, and can eventually stall and fall back onto the galaxies, forming a galactic fountain of recycled gas. This process redistributes gas from the center of a galaxy to its outskirts, further accelerating the transformation of the galaxy itself into a thin disk: galactic structure shapes galactic fountains, and vice versa.

Just as for the other simulations of the TNG family, the team of scientists creating TNG50 (based at Max Planck Institutes in Heidelberg and Garching, Harvard University, MIT, and the CCA) will eventually release all simulation data to the astronomy community at large and to the public. Then, astronomers all over the world will be able to make their own discoveries in the TNG50 universe – and possibly find additional examples of emergent cosmic phenomena, of order emerging from chaos.

Annalisa Pillepich

in collaboration with

Dylan Nelson (Max Planck Institute for Astrophysics, Garching, Germany)

Annalisa Pillepich et al. 2019, “First results from the TNG50 simulation: the evolution of stellar and gaseous discs across cosmic time” in The Monthly Notices of the Royal Astronomical Society, Vol. 490, 3196. DOI: 10.1093/mnras/stz2338

Dylan Nelson et al. 2019, “First results from the TNG50 simulation: galactic outflows driven by supernovae and black hole feedback” in The Monthly Notices of the Royal Astronomical Society, Vol. 490, 3234. DOI: 10.1093/mnras/stz2306

III.11 Highlights

Star formation in the center of the Milky Way came in bursts

Observations of the center of our home galaxy have allowed astronomers to reconstruct, for the first time, the history of star formation in the center of the Milky Way. Previously, it had been assumed that stars in the so-called nuclear stellar disk had formed continuously over the past billions of years. Instead, the new results imply a burst of star formation activity more than eight billion years followed by a quiet period, and then another burst of activity about one billion years ago. The re-written evolutionary history has consequences for the formation of the bar-shaped feature of our galaxy's disk.

Astronomers have uncovered the previously unknown history of the stars near the center of our galaxy. Their work shows that the stars in question formed in two waves: more than 90 % of the stars formed at least eight billion years ago. A second batch, responsible for around 5 % of the stars, formed in a short amount of time around one billion years ago. Between the two bursts of activity, there was a long quiescent period with hardly any new stars forming at all.

Fig. III.11.1: Image of the Milky Way's central region with an angular resolution of 0.2 arcseconds, taken with the HAWK-I instrument on ESO's Very Large Telescope for the stellar survey in the nuclear disk undertaken by Francisco Nogueras-Lara et al.

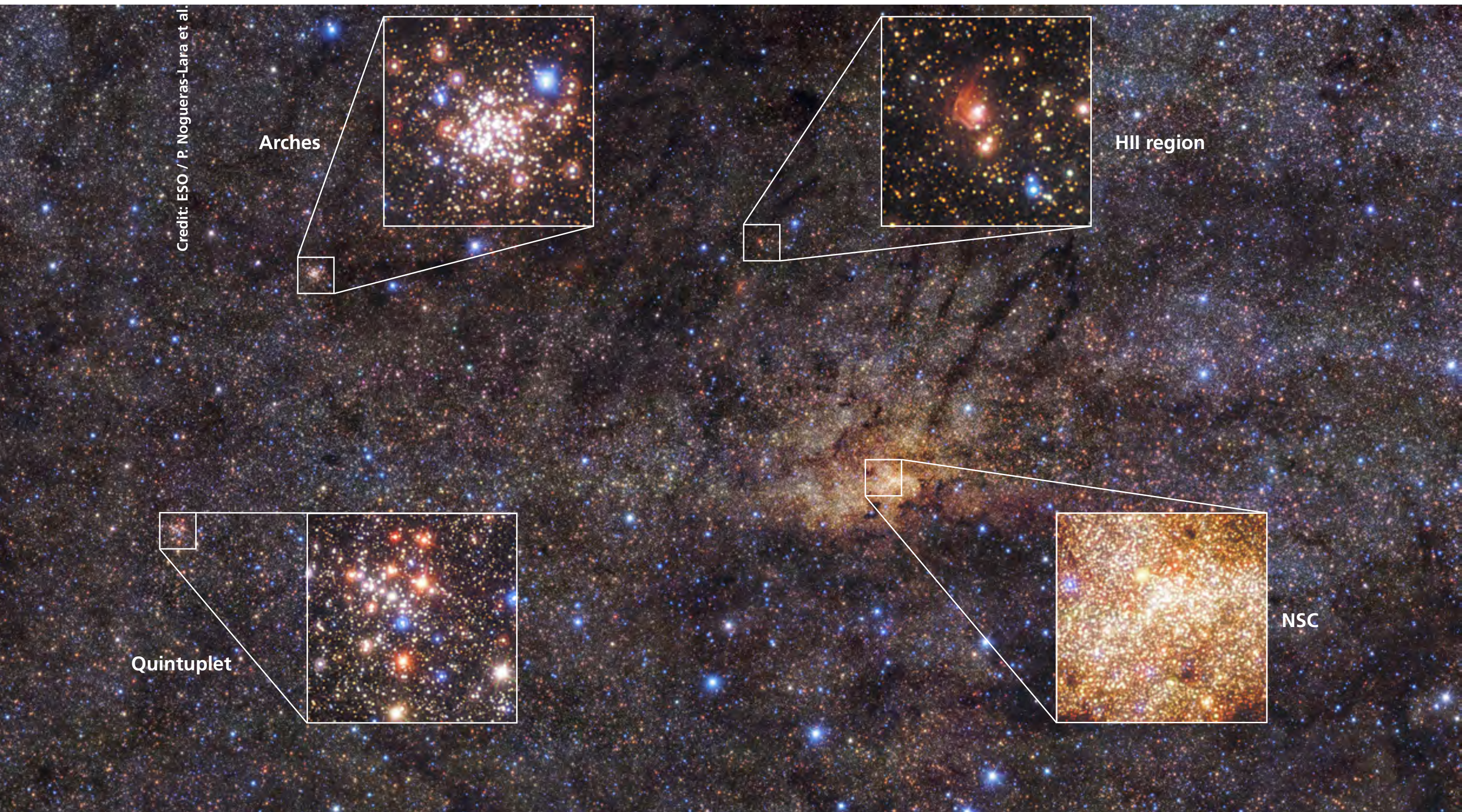
The stars in question belong to a dense, disk-shaped region with a diameter of about 1000 light-years (roughly 1 % of the diameter of the Milky Way's majestic disk of stars), known as the nuclear disk. This disk surrounds the Milky Way's innermost nuclear cluster of stars and its central supermassive black hole.

Bursts of star formation activity

With their result of two intense episodes of star formation, the researchers have rewritten part of our home galaxy's history: Previously, it had been assumed that the stars in the central region of the Milky Way had formed gradually over the past billions of years. The new timeline has consequences for a number of other astronomical phenomena.

Notably, it constrains the growth history of our galaxy's central black hole. Gas flowing into the central regions of our galaxy drive both star formation and the increase in central black hole mass. The newly reconstructed star formation history indicates that our central black hole is likely to have reached most of its present mass earlier than eight billion years ago.

The brief, but intense burst of star formation activity one billion years ago is likely to be one of the most



energetic events in the history of our galaxy. Hundreds of thousands of newly formed massive stars would have exploded as supernovae within millions of years.

The results also force astronomers to rethink another fundamental feature of our galaxy. The Milky Way is a barred spiral galaxy, with an elongated region estimated between 3000 and 15 000 light-years long linking the inner ends of its two major spiral arms. Such bar structures are thought to be very efficient at funneling gas into a galaxy's central region, which would lead to the formation of new stars.

The billions of years without star formation in the nuclear galactic disk forces astronomers to rethink this scenario. During those quiet years, gas was evidently not entering the Galactic center in sufficient amounts. Either the galactic bar has come into existence only recently, or such bars are not as efficient in funneling gas as is commonly assumed. In the latter case, some event – like a close encounter with a dwarf galaxy – must have triggered the gas flow towards the Galactic center about one billion years ago.

Reconstructing the formation history of the Galactic center

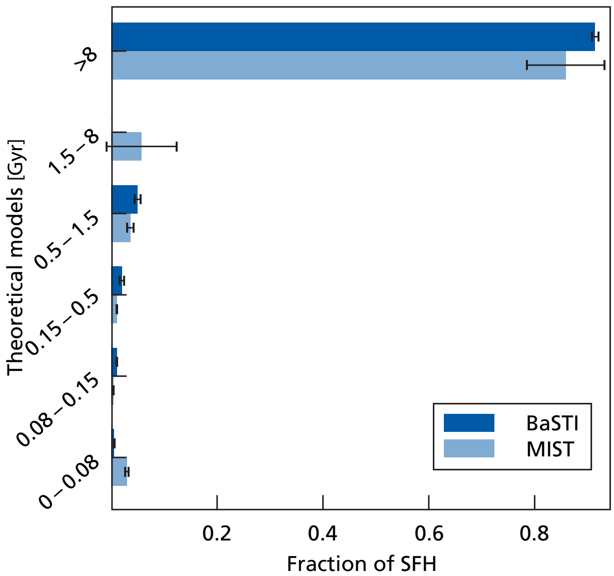
The reconstruction of the history of the nuclear Galactic disk makes use of some of the fundamental insights of astronomers into star formation. Stars only live for a certain time span, which depends on their mass and chemical composition.

Whenever many stars have been born at the same time, which is a common occurrence, astronomers can look at the ensemble, plot the star's brightness against the reddishness of their color ("color-magnitude diagram") and deduce how long ago the ensemble was formed. One among several age indicators is the "red clump" of stars that have already begun to fuse helium in their core regions. From the average brightness of stars in that clump, one can deduce the age of that group of stars.

Challenges of observing the Galactic center

But there is a catch: All those techniques require astronomers to study separate stars. For the Milky Way's central regions, that is a highly challenging task. As seen from Earth, the Galactic center is hidden behind gigantic clouds of dust, requiring infrared observations to "look through" the clouds.

But then, such observations are bound to see too many stars in the Milky Way's center! The Galactic center is very dense, with between a thousand and a hundred thousand stars in a cube with a side-length of one light-year. When astronomers observe very dense star fields of this kind, those stellar disks will overlap in the telescope image. Dissecting such fields into separate stars



Credit: F. Nogueras-Lara et al.

Fig. III.11.2: Star formation history (SFH) of the Milky Way's central region derived by two different sets of stellar evolutionary models (BaSTI: Bag of Stellar Tracks and Isochrones, MIST: MESA Isochrones & Stellar Tracks). Over 80% of the stars formed between 8 and 13.5 billion years ago. This initial formation epoch was followed by a quiescent period of more than 6 billion years duration, which ended with remarkable event 600 million or 1 billion years ago (depending on the models used), during which ~5% of the stellar mass formed. The past 30 million years have been relatively active.

is difficult – but necessary if you want to reconstruct the formation history of the Galactic center.

The right instrument for the job

Given those challenges, when Rainer Schödel (Instituto de Astrofísica de Andalucía, PI of the GALACTICNUCLEUS survey), MPIA's Nadine Neumayer and their colleagues began planning to tackle the history of our Milky Way's central region in late 2014, they knew they would have to find the right instrument for the job. They would need a near-infrared instrument with a large field of view, able to observe the Milky Way's central region, which is in the Southern Sky. And there was such an instrument: HAWK-I, an infrared camera at the 8 meter Very Large Telescope at the Paranal Observatory of the European Southern Observatory (ESO) in Chile.

For their GALACTICNUCLEUS survey, the astronomers observed the Galactic center region with HAWK-I for 16 nights managing to obtain accurate photometry of more than three million stars. Using a special technique known as holographic imaging, the astronomers were able to distinguish between stars as little as 0.2 arc seconds apart. With this accuracy, you could distinguish two one-cent coins viewed from a distance of more than 8 kilometers. Two clearly visible "red clumps" in the resulting color-magnitude diagram allowed for the reconstruction of the formation history of the Galactic nuclear disk.

As a next step, the astronomers are now studying the influence of dust on their observations (extinction and reddening). Taking into account the effect of dust should allow for even more precise reconstructions of the history of our galaxy's central regions in the future.

Francisco Nogueras Lara and Nadine Neumeyer

in collaboration with

Rainer Schödel, A. Teresa Gallego-Calvente, Eulalia Gallego-Cano, Banafsheh Shahzamanian, Hui Dong (Instituto de Astrofísica de Andalucia), Michael Hilker (ESO), Francisco Najarro (CAB-CSIC/INTA), Shogo Nishiyama (Miyagi University Sendai), Anja Feldmeier-Krause (University of Chicago), Julien. H. V. Girard (STScI), Santi Cassisi (INAF-Astronomical Observatory of Abruzzo).

Part of this work was supported by the subgroup B8 of the Collaborative Research Center, SFB 881 "The Milky Way System" at Heidelberg University

F. Nogueras-Lara et al. 2020, "Early formation and recent starburst activity in the nuclear disk of the Milky Way" in Nature Astronomy, Vol. 4, 377. DOI: 10.1038/s41550-019-0967-9

F. Nogueras-Lara et al. 2020, "GALACTICNUCLEUS: A high-angular-resolution JHKs imaging survey of the Galactic centre – II. First data release of the catalogue and the most detailed CMDs of the GC" in Astronomy & Astrophysics, Vol. 631, A20. DOI: 10.1051/0004-6361/201936263

III.12 Highlights

Feeding the first supermassive black holes

Supermassive black holes in the centers of galaxies are increasingly found at distances that correspond to an age of the Universe of just a few hundred million years. A group of astronomers led by Emanuele Paolo Farina has now gained important insights into how these objects may have grown so rapidly. They have detected extended hydrogen clouds around 12 of 31 observed active black holes and their host galaxies, that provide sufficient food.

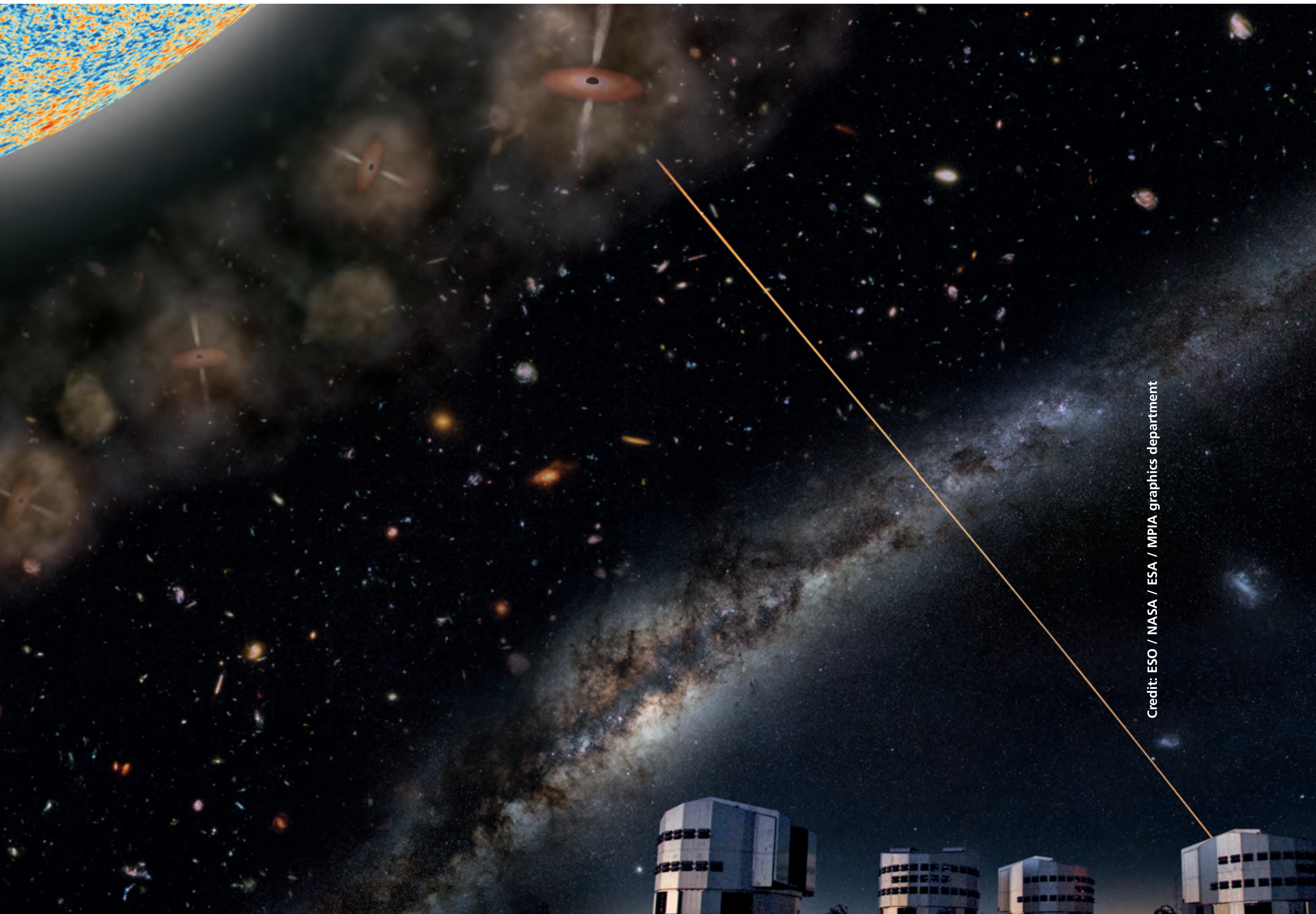
Quasars are among the brightest long-lived objects in the Universe. Therefore, they can be detected even at longest distances in the cosmos. With increasing distance to the observed objects astronomers simultaneously look further and further back into the cosmic past.

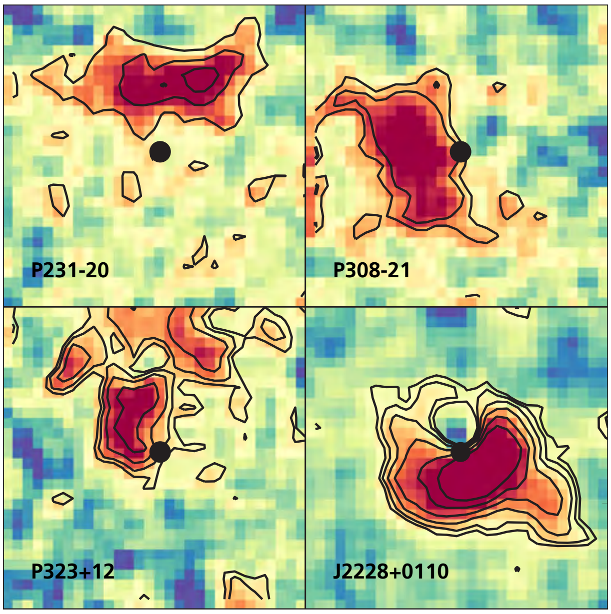
Fig. III.12.1: Artistic representation of the observation of distant quasars in the early Universe. The light captured by the telescopes took about 12.5 billion years from the source to Earth. Astronomers therefore see these objects only a few hundred million years after the Big Bang. The current study shows that the host galaxies of these massive black holes are surrounded by clouds of hydrogen gas.

Quasars are supermassive black holes with masses of more than one billion suns in the centers of galaxies into which flows gas and other material. This gas heats up so strongly that it radiates extremely brightly.

How did the first supermassive black holes grow?

The first quasars already existed a few hundred million years after the Big Bang. But how these black holes could grow to such large masses in the short period after the first stars existed is one of the greatest astronomical puzzles. In addition, the host galaxies of these quasars form new stars at a rate 100 times higher than the Milky Way and other nearby galaxies. Simulations such as Illustris TNG let astronomers assume that enormous amounts of gas from the intergalactic medium are constantly being exchanged for this purpose, so that the host galaxies of the young quasars should be enveloped in clouds of hydrogen. Previously, only a handful of quasars have





Credit: E. Farina / MPIA

Fig. III.12.2: Reconstructed images showing the diversity of the distribution of hydrogen gas (black contours and red colors) near four high-redshift quasars and their host galaxies. The contributions of the bright quasars marked by black dots have been removed. The field of view of these images is 6" × 6" (1" = 1 arc second), which corresponds to a physical size of about 100000 light years.

been studied in this way. In a paper published earlier this year, a group of scientists led by MPIA's Alyssa Drake mapped appreciable quantities of gas around four distant quasars.

Building on the preliminary work of Fabian Walter and Bram Venemans (both MPIA), Emanuele Paolo Farina, a researcher at both the MPIA and the Max Planck Institute for Astrophysics (MPA), initiated the REQUIEM (Reionization Epoch QUasar InvEstigation with MUSE) project. This systematic survey looks for signs of gas clouds around the first quasars that existed when the Universe was no more than a billion years old. An evaluation of the first 31 examined objects led to the detection of 12 extended and surprisingly dense hydrogen clouds. They all enclose the host galaxies and are gravitationally bound to them. The amount of gas is sufficient to feed the activity of the quasars and the increased formation of stars.

Large gas clouds reveal themselves by a glow in UV light

The astronomers discovered the hydrogen clouds by their characteristic glow in UV light. The most likely explanation for the shining gas is the mechanism of fluorescence. The hydrogen converts the energy-rich radiation of the quasar into light with a specific wavelength, which is noticeable by a glimmer. Given the large distance and the associated cosmic redshift, earthbound telescopes perceive the glow as red light.

These clouds were detected by the spectrograph MUSE (Multi Unit Spectroscopic Explorer) at the Very Large Telescope (VLT) of the European Southern Observatory (ESO) in Chile. In addition to the spatial distribution of the hydrogen signal, MUSE also measures the velocity of the gas along the line of sight. From the analysis, the scientists conclude that the gas may be flowing radially to the centers of the galaxies, feeding the black holes.

We are just at the beginning

It is only through the development of new, powerful instruments that we can now study the conditions at the beginning of the evolution of the first supermassive black holes and galaxies. The discovery of these widespread hydrogen gas clouds is an important step towards understanding how those black holes could have grown within a few hundred million years since the first stars appeared. But more work is needed – the current studies are just the first step towards explaining how the first supermassive black holes were able to develop so rapidly. It's already clear, though, that new instruments will play a key role in solving this and similar puzzles – instruments like MUSE at present, and the James Webb Space Telescope in future.

Emanuele Paolo Farina (also MPA), Alyssa Drake, Fabian Walter, and Joseph F. Hennawi

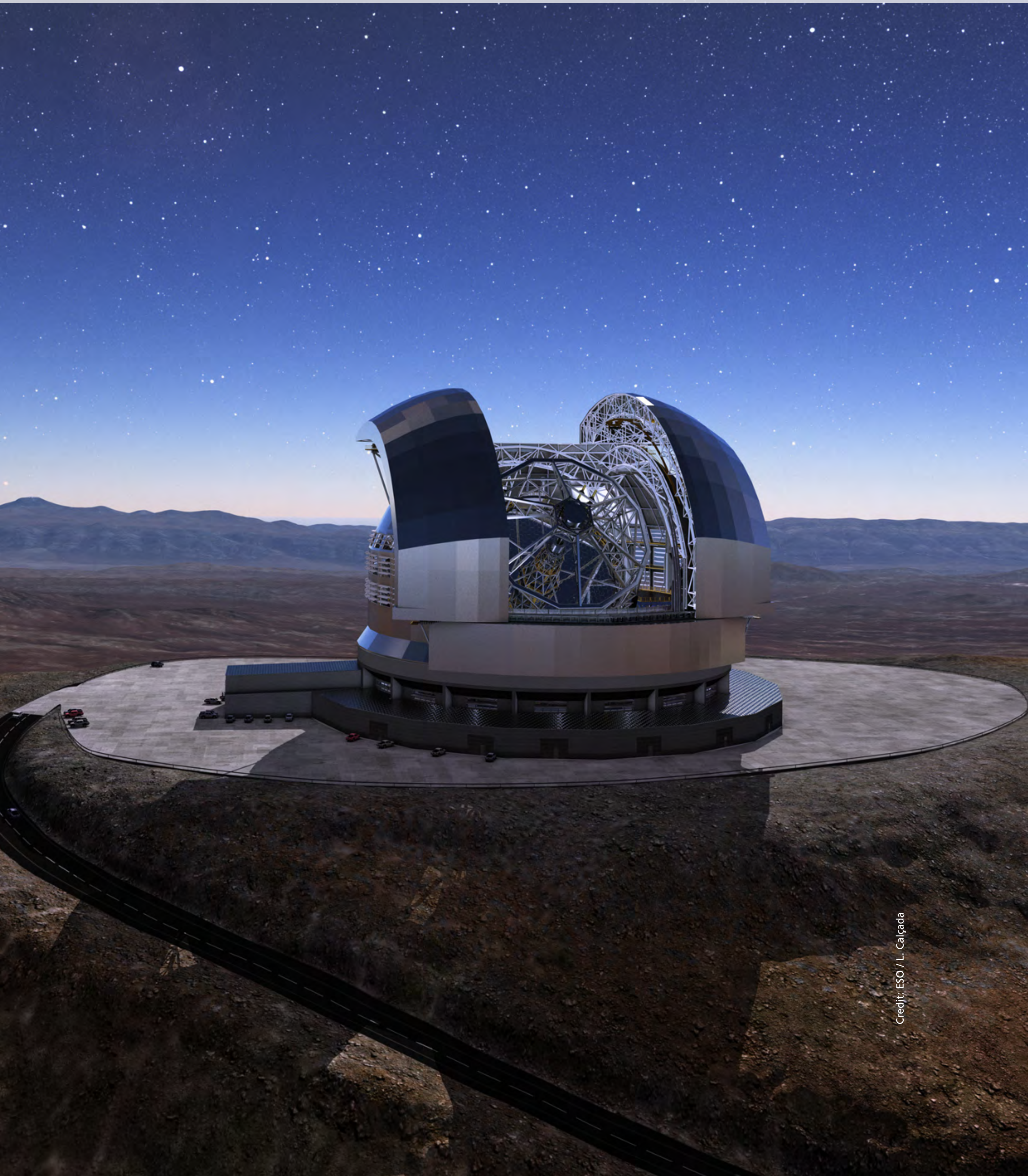
in collaboration with

Fabrizio Arrigoni-Battaia and Tiago Costa (MPA) and the REQUIEM Collaboration

Emanuele Paolo Farina et al. 2019, "The REQUIEM Survey. I. A Search for Extended Ly Nebular Emission Around 31 $z > 5.7$ Quasars" in The Astrophysical Journal, Vol. 887, 196. DOI: 10.3847/1538-4357/ab5847

Alyssa B. Drake et al. 2019, "Ly α Halos around $z \sim 6$ Quasars" in The Astrophysical Journal, Vol. 881, 131. DOI: 10.3847/1538-4357/ab2984

IV. Instrumentation and Technology



Credit: ESO / L. Calçada

IV.1 Overview

Instrumentation for Ground-based Astronomy

In 2019, MPIA activities in the area of ground-based instrumentation concentrated on spectroscopy and high fidelity imaging for the future Extremely Large Telescope (ELT) of the European Southern Observatory (ESO), on multi-object spectroscopy for ESO's VISTA telescope, a high-spatial-resolution imager for the Large Binocular Telescope (LBT), survey instrumentation for Calar Alto, and a contribution to a new imaging and spectroscopy instrument for the 2.5 meter Nordic Optical Telescope on La Palma. MPIA's principal instrumentation projects consist of building two of the three first-light instruments for the ELT, a next generation telescope with a main mirror 39 meters in diameter.

Instrumentation for the Large Binocular Telescope (LBT)

The largest ongoing MPIA instrumentation project up to now has been the near-infrared beam combiner LINC-NIRVANA (L-N). This instrument was finally installed at the LBT in late September 2016. It saw nine separate commissioning runs up to 2019, and one in February 2020, with three more to come. 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.

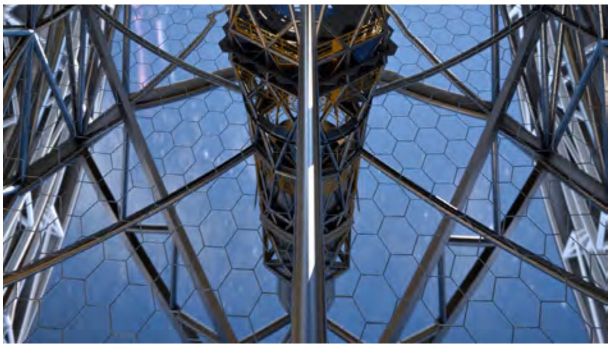
Scientific targets of LINC-NIRVANA range from supernova cosmology, galaxy formation and extragalactic stellar populations and star formation to extrasolar planets, stellar multiplicity, the structure of circumstellar disks and the imaging of Solar System planets and their atmospheres.

Instrumentation for ESO's VISTA telescope

Project 4MOST, which MPIA joined in 2014, is a multi-object spectrograph for the 4.1 meter VISTA telescope at ESO's Paranal observatory. While the main part of the Final Design Review had already been completed in April 2018, the review was only completed as a whole in February 2019. After that, MPIA delivered its contributions to the partner institutes in the course of

Fig. IV.1.1: The ELT construction site in early 2020, with the foundations for the dome and main structure clearly visible.

2019. The project is led by the Astrophysical Institute Potsdam. MPIA is responsible for the instrument control electronics. It also provides the carbon-fibre housing of the metrology camera of the instrument. 4MOST 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 its field of view. Chapter IV.2 presents a more detailed overview of the 4MOST project.



Credit: ESO / L. Calçada / ACe Consortium

Fig. IV.1.2: Artist's rendering of the ELT primary mirror, based on the detailed construction design for the telescope.

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

After MPIA's formal involvement in the Calar Alto Observatory had come to an end in December 2018, the institute has continued to cooperate with Calar Alto in the framework of an upgrade of the PANIC instrument as well as in the scientific exploitation of the guaranteed-time observations from an exoplanet survey carried out with the instrument CARMENES. MPIA will continue to be involved in these two endeavors until 2021 for PANIC, and for about 2–3 more years for the CARMENES survey, as in the meantime an extension of this planet search program has been approved.

The Panoramic Near-Infrared Camera (PANIC), which had previously been operational between April 2015 and mid-2018, is a wide-field general purpose instrument for the CAHA 2.2 meter telescope. PANIC was a joint development of the MPIA and the Instituto de Astrofísica de Andalucía. Originally, with four HAWAII-2-RG detectors, it provided a field of view of $30'' \times 30''$ (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 HAWAII-4-RG detector, which will cover the same field of view. Reinstallation on Calar Alto and commissioning are planned for 2021.

CARMENES is a pair of high-resolution Échelle Spectrographs at the CAHA 3.5 meter telescope, operating, respectively, at visual and infrared wavelengths. It was built by a consortium of five German and six Spanish institutions. With 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, almost 70 % of the guaranteed time was used up; the remaining observations will be carried out until mid-2020.

In November 2018, a memorandum of Understanding was signed between MPIA and the Niels Bohr Inszitute of the University of Copenhagen. Thus began a collaboration for a new project for the 2.5 meter Nordic Optical Telescope (NOT), which is located at the Roque de los Muchachos Observatory on La Palma. The instrument, which is called the NOT Transient Explorer (NTE), will

Credit: ESO / P. Lapeyre

be a medium-resolution imager and spectrograph covering wavelengths from the near-UV to the near-infrared. Its goal is to enable rapid follow-up of transient phenomena such as gamma-ray bursts and supernovae. MPIA contributes to this project three systems of the read-out electronics and software that had previously been developed at the institute. Also, MPIA will be responsible for characterizing the infrared detectors. Two of the three read-out units were manufactured by December 2019. The NTE instrument is slated for installation at the NOT in mid-2022.

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. IV.1.3 : The band of the Milky Way lights up the night sky above the construction site of the Extremely Large Telescope (ELT) in the Chilean Atacama Desert in July 2019.

MPIA participates in two of the ELT's three first-light instrumentation projects: METIS and MICADO. In May 2019, METIS passed its preliminary design review and entered the final desgin phase. MICADO had already passed its preliminary design review in November 2018. At the time of writing, the final design reviews are planned for April 2021 for MICADO, and for April 2022 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

Credit: ESO / M. Zamani

Credit: ESO

Fig. IV.1.4: Artist's rendering of the ELT in full operation, with laser guide stars to help its adaptive optics system.

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

IV.2 Overview

4MOST – The 4m Multi-Object-Spectroscopic Telescope

The 4MOST project converts the 4.1m VISTA telescope at Paranal, Chile, to a multi-object spectroscopic telescope. The facility is set to start operations in 2023, and is laid out for a lifetime of 15 years. The main science driver for the telescope was the need to complement existing and upcoming space missions like Gaia, eROSITA and EUCLID with spectroscopic data. The consortium partners have developed ten survey programs, which will be supplemented by community surveys. Taken together, 4MOST observations will address a broad range of astronomical questions, furthering our understanding of the Milky Way, galaxy formation, and cosmology. As a major contributor within the 4MOST consortium, MPIA leads one of the consortium surveys and has undertaken to build the facility electronics.

The instrument

As shown in Figure IV.2.1, the 4MOST facility consists of a wide field corrector, a fiber positioner which connects with long science fibers to multiple spectrographs, a metrology system, and a calibration unit. All of this is operated by the facility control electronics and software. The design of the components is driven by the science requirements of the key consortium surveys.

As an example, the size of the wide field corrector field of view amounts to 2.5 degrees, which allows a survey to cover a field of more than 17 000 square degrees twice, over five years of operation. A unit with such a field demands optical lenses that are of considerable size, and challenging in both manufacture and handling (top left of Figure IV.2.2). The major goal of 4MOST is to observe about 20 million objects with a spectroscopic resolution of 6 500, and about three million objects with a resolution of 20 000. This demand is met by three spectrographs, each one fed by 812 fibers. Two of the spectrographs provide the lower-resolution data, and one the high-resolution data. The fiber positioning system (bottom left of Figure IV.2.2) is based on the well-established "Echidna" technology, where fiber spines are tilted by piezo elements to acquire the objects. The spines look like the spikes of the Australian echidna.

Instrument parameter	Design value
Field of view (hexagon)	~4.2 square degrees (∅ = 2.6 degrees)
Accessible sky (zenith angle <55 degrees)	>30 000 square degrees
Expected on-target fiber hours per year	LRS: > 3 200 000 h/yr, HRS: > 1 600 000 h/yr
Multiplex fiber positioner	2436
Low-Resolution Spectrographs LRS (×2) Resolution Number of fibers Passband Velocity accuracy Mean sensitivity 6×20 min mean seeing New moon, S/N = 10 Å^{-1} (AB-magnitude)	 <R> = 6500 812 fibers 3700 – 9500 < 1 km s^{-1} 4000 Å: 20.2, 5000 Å: 20.4, 6000 Å: 20.4, 7000 Å: 20.2, 8000 Å: 20.2, 9000 Å: 19.8
High-Resolution Spectrograph HRS (×1) Resolution Number of fibers Passband Velocity accuracy Mean sensitivity 6×20 min mean seeing New moon, S/N = 10 Å^{-1} (AB-magnitude)	 <R> = 20 000 812 fibers 3926 – 4 355 Å, 5160 – 5730 Å, 6100 – 6790 Å < 1 km s^{-1} 4200 Å: 15.7, 5400 Å: 15.8, 6500 Å: 15.8
Smallest target separation	15 arcseconds on any side
# of fibers in random ∅ = 2 arcminutes circle	≥ 3
Fiber diameter	∅ = 1.45 arcseconds

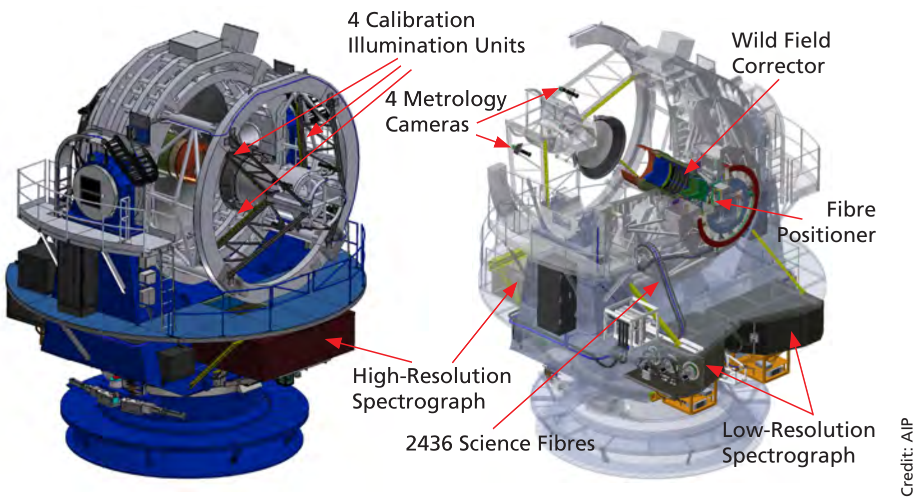


Fig. IV.2.1: CAD model of the VISTA telescope with the 4MOST instrument. The left side shows the facility looking onto the primary mirror. The right side looks from the back of the mirror cell. While here the telescope is kept transparent, the 4MOST components are solid to demonstrate how they are distributed over and around the telescope structure.

MPIA hardware contribution

MPIA is in charge of building the facility control electronics for the 4MOST instrument. The electronics move motors like the spectrograph shutters or the atmospheric dispersion corrector. They monitor the temperature and pressure in and outside the spectrograph, control the vacuum and cryostat for the detectors and switch calibration unit and metrology system components. Figure IV.2.3 shows the two final instrument cabinets during assembly in the MPIA integration area.

Most of the control units are shared between the individual spectrographs and sub-systems. Such centralized control approach was necessary because of weight, power and place constraints and kept also the overall costs for the control electronics lower. But such approach introduced a logistical challenge. Apart from MPIA, five other consortium partners, distributed over Europe and one even located in Australia, provide hardware, which is interfaced to the control electronics. The sub-systems are assembled in parallel during the manufacturing and integration phase. Hence, the control units are needed at different locations, in order to operate the sub-systems.

This raised the question of how to satisfy all partners without ending up with a sequential approach, sending the control electronics to each partner in turn, which would have cost too much time. Luckily, each module in the electronics cabinets has a line replacement unit, for rapid exchange in case of failure. Later, when the instrument is in operation, this is meant to keep the downtime. But it also helped us in managing the logistics: We built the original unit as well as the spare units in one batch, early on in the project.

We then equipped the final cabinets with the original units, providing the assembly to the group building the high resolution spectrograph, while a test cabinet was equipped with the spare units and then sent to the location of the low resolution spectrograph integration. So far, the remaining partners were able to work with sub-units, sent out in sequence.

A complication of this approach is that each of the usual change requests that come up during such test phases now needs to be retrofitted between the original and the spare system. Altogether this creates more work load than usual in planning, in support and in reworking. But overall, our strategy has worked out: We have kept the 4MOST project advancing at a good pace.

The metrology camera housing

The metrology cameras control the fine positioning of the fiber spines in the focal plane. At the spectrograph slit, light can be fed into the fibers, in such a way that they shine in the focal plane. Cameras attached at the secondary mirror spider look down through the wide field corrector on the fibers in the focal plane (cf. Figure IV.2.1). After the cameras are calibrated so as to take image distortion into account, the images can be used to map all fibers properly to their proper positions in the focal plane, and thus to make sure that they capture light from the precise position on the sky where their specified target objects are located – a functionality that is crucial to 4MOST.

However, at some point of the project, a decision had to be made whether the housing of the four metrology cameras should be outsourced or provided by one of the partners. The requirements on weight and temperature stability for such housing are very demanding. Changes in other MPIA projects opened a window of opportunity to utilize MPIA's expertise in lightweight design with carbon fiber. A carbon fiber housing with titanium mounts, designed to meet the temperature stability requirement was proposed and accepted. The final dimensions of each mount had to be adjusted individually to each lens.

Credit: *Top:* AIP, *Bottom:* AAO

Fig. IV.2.2: *Top:* Lens 3 of wide-field corrector, as presented at the local acceptance review. *Bottom:* The "Echidna" fiber positioner on the test stand.

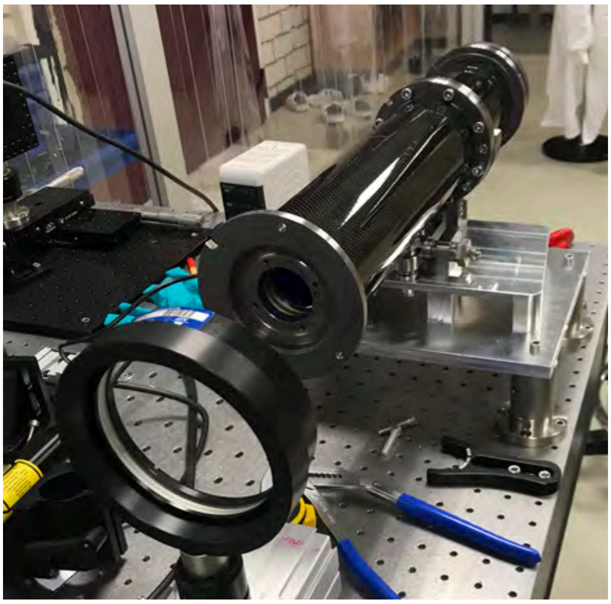
Credit: MPIA

Fig. IV.2.3: The two electronics cabinets for 4MOST in the MPIA integration area during assembly.

Titanium is a very demanding material, and difficult to process. Previously, the MPIA precision mechanics workshop had not too much of a track record with titanium, so this was a great opportunity for them to gain additional experience. With the help of an aluminum prototype, the manufacturing process was tested and optimized. The final adjustment and flattening of the mounts had to be done after they had already been glued to the carbon tubes. The milling for this last step was very delicate and was done dry, in order to avoid impact on the carbon fiber tubes. We were able to deliver the housings to our partners in Potsdam in time, and they were impressed with the quality of the work. The units were then equipped with the lenses. Currently, they are under testing for image quality over the full temperature range of operation (see Figure IV.2.4). All the tests so far have shown the units to meet or even to exceed the stringent requirements.

Wolfgang Gaessler for the MPIA 4MOST Team

Fig. IV.2.4: One of the metrology cameras in its housing, with the opto-mechanical components installed, on the test stand in Potsdam.

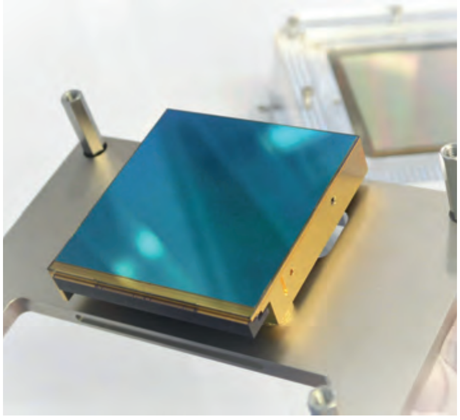


Credit: AIP

IV.3 Instrumentation at MPIA

Overview of current projects

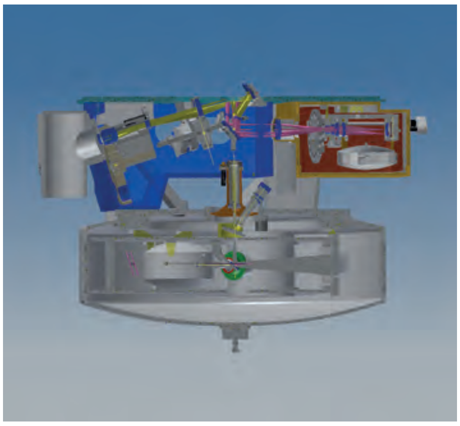
Astronomical instruments have different strengths and specializations. Here, we list **ongoing MPIA instrumentation projects for the year 2019**. Almost all of the instruments are cameras for producing astronomical images, spectrographs for analyzing the color components of light, or combinations thereof.



PANIC-4K

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

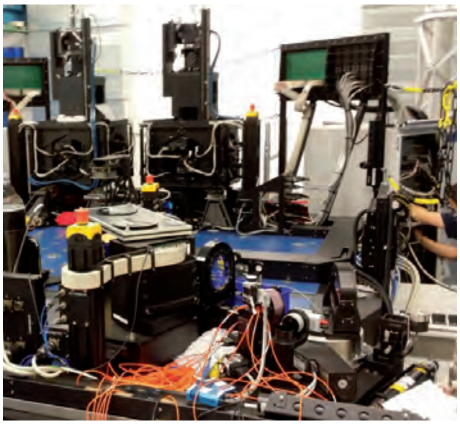
Telescope	2.2 meter Telescope, Calar Alto, Spain
Wavelength range	Near-infrared, 0.9 – 2.15 µm
Targets	Multipurpose wide-field survey imager
Resolution	Seeing limited
Special features	Large field-of-view – size of the full Moon
MPIA contribution	Purchase, integration, and testing of novel 4×4 K near-infrared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



NTE

Nordic Optical Telescope Transient Explorer

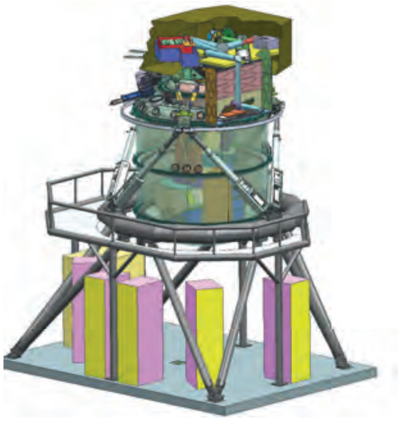
Telescope	2.5 meter Nordic Optical Telescope, La Palma, Canary Islands
Wavelength range	UV, visible, near-infrared, 334 – 2200 nm (imaging and spectroscopy)
Targets	Transient phenomena, gamma-ray bursts, gravitational wave sources, kilo- and supernovae
Resolution	Imaging: 0.18″/pixel, field-of-view 6′;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



LINC-NIRVANA

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

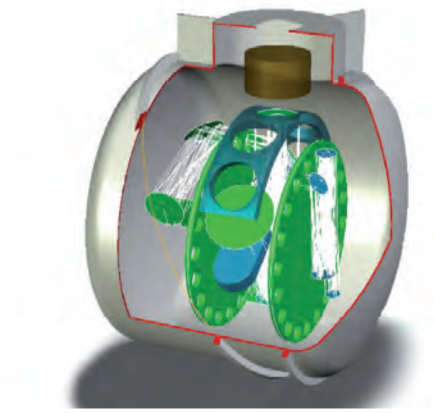
Telescope	Large Binocular Telescope, Mt. Graham, Arizona
Wavelength range	Near-infrared, 1.1 – 2.4 µm
Targets	Star clusters, black holes, protoplanetary disks
Resolution	30 – 90mas (wavelength-dependent) as adaptive optics imager
Special features	Particularly wide-field adaptive optics
MPIA contribution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



METIS

Mid-infrared ELT Imager and Spectrograph

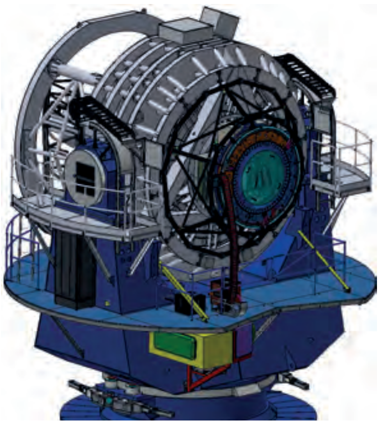
Telescope	Extremely Large Telescope
Wavelength range	Mid-infrared (3 – 9 µm = L/M, N, Q bands)
Targets	Disks, exoplanets, supermassive black holes, high-*z* galaxies
Resolution	16 – 74 mas depending on wavelength
Special features	Can do coronagraphy and polarimetry
MPIA contribution	Imager and single-conjugate adaptive optics
Status	Working toward preliminary design review in April 2020



MICADO

Multi-AO Imaging Camera for Deep Observations

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



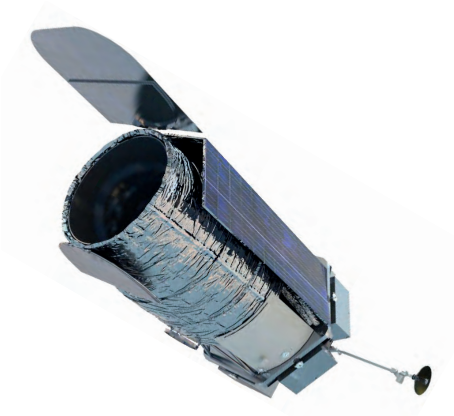
4MOST

4 meter Multi-Object Spectroscopic Telescope

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

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

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



CORONAGRAPH INSTRUMENT (CGI)

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

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

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

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

Fig. IV.3.1: MPIA is contributing to the 4MOST spectrograph, which will be installed at the VISTA survey telescope at ESO's Paranal observatory in Chile.

Credit: ESO

IV.4 Highlight

Technical Departments

METIS Real-Time Computer Prototyping

As part of the Mid-infrared ELT Imager and Spectrograph (METIS) team, we are developing a real-time computer (RTC) that runs several control loops for Single Conjugate Adaptive Optics (SCAO). The ELT is ESO's next generation telescope, with a mirror diameter of 39 meters, currently under construction. Adaptive optics is needed in order to overcome a natural limitation of ground-based observations: AO systems counteract the image distortions produced by turbulence in the Earth's atmosphere. To that end, the image of either a natural star or an artificial laser guide star is monitored, and suitable corrections made by the precise deformation of a deformable mirror, or deformable mirrors, that are part of the telescope setup.

In order to produce real-time correction, the control loops involved need to be very fast. The control loop with the tightest timing constraints is the wavefront control loop. In each loop cycle, the RTC receives one image from the wavefront sensor (WFS). From the image, it computes commands for the correction of the wavefront and sends them to the adaptive, deformable mirrors of the ELT. In order to provide optimal quality for science observations, we need to minimize the latency between wavefront measurement and application of mirror commands. Since the WFS acquires images with a rate of up to 1 kHz, that is, 1000 times per second, it is necessary for the RTC to command the adaptive mirrors at the same rate. It is of paramount importance that the RTC meet this hard real-time requirement.

The sheer scale of the ELT in terms of the number of actuators driven by the RTC requires unprecedented computing power in order to run the wavefront control loop in real-time. As specified at the preliminary design review (PDR), the RTC requires during its operations a steady memory throughput for accessing configuration parameters that corresponds to the content of about 760 full CD-ROMs per second (approx. 563 Gbyte/s). The large number of configuration parameters is due to the impressive number of 5316 actuators that serve to deform the mirror M4 of the ELT.

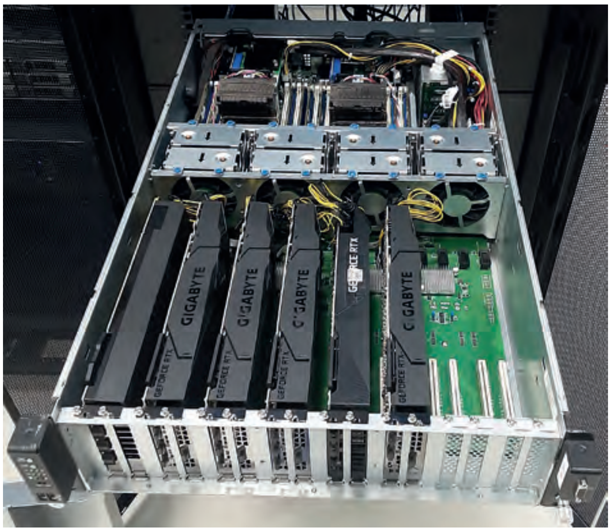

Credit: MPIA

Fig. IV.4.1: The METIS SCAO RTC prototype hardware containing six GPUs of type Nvidia GeForce RTX 2080 Ti.

Our RTC prototype is based on computers equipped with graphics processing units (GPU). The prototype hardware can be seen in figure IV.4.1. We tested the RTC performance in a distributed setup that we expect to resemble basic parts of the final installation of the RTC in the ELT. In order to be able to correlate events in this setup, we deployed a grandmaster clock as a reference clock via Precision Time Protocol (PTP), allowing us to synchronize all computers involved in the experiment. With a total of six high-end consumer GPU cards, our RTC prototype has demonstrated its ability to fulfill the demanding real-time requirements.

Martin Kulas, Florian Briegel and Horst Steuer
for the MPIA instrumentation software department

V. Academics, Education and Public Outreach

Credit: HdA

V.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. Both the directors and the research group leaders are involved in teaching at Heidelberg University. For instance, this year MPIA scientists were involved in teaching the Cosmology Block Course (Annalisa Pillepich) and the Stellar Astrophysics Block Course (Maria Bergemann), as well as Advanced Seminars on the Physics of Star Formation (Thomas Henning) and the Physics of Exoplanets and Planet Formation (Hubert Klahr).

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

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.

Since IMPRS-HD began in 2005, the year 2019 is the 15th year of IMPRS activity. Thus, it is the 15th generation of IMPRS students that has started their academic year in 2019. Just as in 2018, the 2019 IMPRS student generation is very strong in numbers: overall 29 new doctoral students arrived this year. Of those students, 12 were members of MPIA, which is almost half of the student generation. The new MPIA PhD students are Tim-

Fig. V.1.1: Participants of the 15th IMPRS-HD summer school.

Credit: C. Fendt, MPIA

Name	Defense Date	Title	Supervisor
Tobias Schmidt	05.02.	Constraints on Quasar Emission Properties from the HeII and HI Transverse Proximity Effect	Hennawi
Anna-Christina Eilers	03.05.	Unravelling 13 billion years of cosmic history with spectroscopic studies: from the Milky Way to the epoch of reionization	Hennawi
Neven Tomicic	15.05.	Probing the cold phase of the interstellar medium and star formation in nearby galaxies	Schinnerer
Yulong Zhuang	26.06.	Diversity of Galactic Stellar Metallicity Gradients and their Origin	Van de Ven
Hans Baehr	05.07.	Formation Criteria and Initial Constraints on Objects Formed in Gravitationally Unstable Disks	Klahr
Natascha Manger	16.07.	High Resolution Simulations of Structure Formation in Turbulent Protoplanetary Disks: A Case Study of the Vertical Shear Instability	Klahr
Mathias Samland	16.07.	High-Contrast Imaging Characterization of Exoplanets	Brandner
Gigi Leung	16.07.	Constraining the nature of dark matter in galaxies with multi-tracer dynamical models	Van de Ven
Sven Buder	16.07.	Spectroscopic Analysis and Chemodynamic Exploration of the Milky Way with Million-Star Survey	Lind
Sarah Leslie	24.07.	The cosmic evolution of star-forming galaxies	Schinnerer
Priscilla Chauke	24.07.	Determining Properties of LEGA-C Galaxies through Spectral Star-formation History Reconstruction	Van de Wel
Mayte Alfaro Cuello	25.07.	The Nucleus of the Sagittarius Dwarf Spheroidal Galaxy: M54	Neumayer
Hector Hiss	15.10	Measuring the Thermal State of the Intergalactic Medium	Hennawi
Mikhail Kovalev	11.11.	NLTE analysis of the Gaia-ESO spectroscopic survey	Bergemann

Table V.1.1: PhDs completed by MPIA students in 2019.

my Delage, Riccardo Franceschi, Matthew Gent, Nicolas Kurtovic, Robert Latka, Ilin Lazar, Kristoffer Nielsen, Sofia Rojas Ruiz, Ekaterina Semenova, Diego Sotilla Ramos, Jonas Syed, and Gideon Yoffe.

Including the newcomers, the total number of IMPRS students since the beginning of the program now amounts to 395. By the end of 2019, 262 of those had graduated with a doctoral degree. About 100 of them are still pursuing their PhD studies.

For the IMPRS fellowship 2019, Sofia Rojas Ruiz (supervisor: Eduardo Bañados) was selected by the IMPRS board. She will work on the topic "Quasars and Galaxies at the Epoch of Reionization".

In 2019, we were again exceptionally successful in spreading information about IMPRS to prospective international candidates: We received 245 applications via the IMPRS-HD channel and 21 via the application channel of the Heidelberg Graduate School for Physics (HGSFP). Of the 245 IMPRS applications, 37% were from females. Of all applications, 116 made it to the extended shortlist, while 40% of the shortlisted applicants were female. As in past years, we received numerous applications from India (66 in total, 27 females), and also from Iran (16 in total, 10 female). Only 29 applications were received from students of German nationality; the numbers from the UK (4 in total), the US (7 in total), and China (19 in total) were low as well. Note that we however received 49 applications from students located in Germany.

Twenty-seven IMPRS students completed their PhD in 2019. The MPIA students among them are listed in Table V.1.1.

The 2019 IMPRS-HD summer school was on the topic of "Instrumentation for Ground-based Optical & Infrared Astronomy." The scientific program was organized by MPIA's Tom Herbst. Invited lecturers were Rebecca

Credit: C. Fendt / MPIA

Fig. V.1.2: Participants of IMPRS-HD seminar. This was the 1st year seminar of the students that have now graduated (see table V.1.1).

Bernstein (Carnegie Observatories, Pasadena), Elizabeth George (European Southern Observatory), Andreas Glindemann (European Southern Observatory), Christoph Keller (Leiden University), and Francois Rigaut (Australian National Observatory, Canberra). This time, 56 participants joined the school, among them 10 local students from Heidelberg. Since the Max-Planck-Haus is unfortunately not available anymore for our school, we were again lucky to be accepted by the "Institut für wissenschaftliches Rechnen" as guests in their "Mathematikon" building on the Neuenheimer Feld university campus.

Christian Fendt

V.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 III of this annual report were all published in the form of press releases, and led to widespread coverage of MPIA research results.

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 V.3. In particular, MPIA scientists make up a significant number of speakers for the public talk series on Königstuhl. This year, there were two special occasions for synergy between HdA and MPIA: Our talk series “Astronomy on Sunday before Noon” this year was dedicated to showcasing MPIA research, as part of our celebrations of the institute's 50th anniversary (cf. Fig. V.2.1). And the exhibition “Astronomy for everybody" had a successful run on Mainau Island, a major German tourist attraction (cf. section V.3).

Fig. V.2.1: Poster for "Astronomie am Sonntagvormittag" ("Astronomy on Sunday before Noon"), which this year, on the occasion of the institute's 50th anniversary, was dedicated to showcase research at MPIA, featuring talks by Wolfgang Brandner, Gesa Bertrang, Hans-Walter Rix, Paul Mollière, Martin Kürster and Nadine Neumayer.

Credit: Background: NASA / JPL / Caltech; Poster: D. Leitner / MPIA graphics department

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 institutes 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.

In addition, MPIA participated this year in the Researchers' Night, on September 27, an EU-funded international celebration of research for which a consortium led by EMBL, and including MPIA and Haus der Astronomie, put in a successful bid for participation. With activities in Heidelberg and Mannheim, linked by a dedicated bus shuttle, the consortium offered a rich set of activities to participants. MPIA researchers presented selected areas of their research in Haus der Astronomie (cf. Fig. V.2.2).

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, with 11 participants in 2019. 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. Sadly, with Klaus Meisenheimer retiring, this year’s internship program, on October 7–11, was the last of its specific kind. Future students are still able to participate in various internship programs at the Haus der Astronomie, of course.

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 (R. Hubele, S. Brümmer and MPIA PhD student Alina Böcker). The purpose of Girls’ Day is to provide female

Credit: C. Liefke / HdA

Fig. V.2.2: Participants of the EU-wide Researchers' Night at Haus der Astronomie, where MPIA astronomers presented selected results of their research. As seen here, the foyer of Haus der Astronomie featured selected interactive exhibits from our exhibition "Astronomie für Alle".

pupils with the opportunity of experiencing professions in which women are underrepresented. For this year's Girls' Day on March 28, 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 far away galaxies. In addition, six girls were given the opportunity to experience a day at the precision mechanical workshop and electronics department of MPIA, working on small construction projects of their own, and learning about possible technical careers related to astronomy (T. Adler, S. Meister, F. Wrhel). 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

V.3 Academics, Education and Public Outreach

Haus der Astronomie
Center for Astronomy Education and Outreach

Haus der Astronomie (HdA; literally "House of Astronomy") is the Center for Astronomy Education and Outreach on 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 2019, the HdA building received more than 15,000 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.

Fig. V.3.1: The HdA's galaxy-shaped building on the MPIA campus on top of the Königstuhl mountain was built by the Klaus Tschira Foundation, and opened its doors in 2011.

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 "Faszination Astronomie" (which loosely translates to "Fascinating Astronomy"), with a total of twelve events (C. Liefke) and "Sunday a.m. Astronomy" with five events on the occasion of the 50th anniversary of MPIA (N. Nielbock). 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 "Saljut 7", "The Dish", "Hidden Figures", "Aufbruch zum Mond (First Man)", "Apollo 13" and "Passengers", introduced by C. Liefke and M. Nielbock.

Credit: D. Elsässer

Fig. V.3.2: Posters for various public events held at Haus der Astronomie in 2019. Design: Daniela Leitner and MPIA Graphics Department

On the occasion of the German national Astronomy Day (“Astronomietag”) on March 30th, HdA and MPIA participated with a talk and a planetarium show focused on light-pollution awareness (T. Herbst, C. Liefke, M. Pössel).

Within the frame of the VIII. International Storytelling Festival, a story night for adults was held at the HdA, accompanied by a planetarium show (N. Fischer, E. Kolar, T. Müller).

Our auditorium was filled with the sound of African music in “Musikalische Sternstunde”, as well as “Nacht der Forschung” thanks to Mokoyaala Chor Heidelberg und Simunye Quartett Südafrika, whose performance was combined with a planetarium show (N. Fischer, T. Müller).

Since 2018, HdA and MPIA have been partners of the Heidelberg branch of the European Researchers’ Night. This EU project, led by EMBL, lasted for 18 months. In this framework, HdA / MPIA organized a public event on September 27th with various activities for the general public which attracted more than 900 visitors (M. Nielbock et al.), and included a concert (see above). To celebrate the 50th anniversary of the first moon landing, HdA hosted German author Michael Büker for a book presentation (“Was den Mond am Himmel hält – Der etwas andere Streifzug zu unserem kosmischen Begleiter”), organised a special talk by Olaf Kretzer (Observatory and Planetarium Suhl) debunking moon landing conspiracy theories, and held a family event “Ein Vormittag auf dem Mond” (N. Fischer, E. Kolar, M. Wetz).

A Leonardo da Vinci evening in November introduced a new event series, which combines the presentation of important figures in the history of astronomy with live music (M. Wetz, S. Brümmer). Altogether, these onsite events drew an audience of more than 4000 visitors.

For particularly interested members of the public and in particular for students at the University of Heidelberg, M. Pössel (with S. Jordan) offered a lecture series “Astronomie für Nichtphysiker: Die Vermessung des Weltalls” (“Astronomy for Non-Physicists: Measuring the Universe”) as an introduction to the methods of astronomy for nonphysicists. Additionally, we offered a one-day workshop on astrophotography for the general public (C. Liefke, M. Penselin). A shorter version of this workshop was offered at Burggespräche des Orion, Schloss Albrechtsberg in Austria.

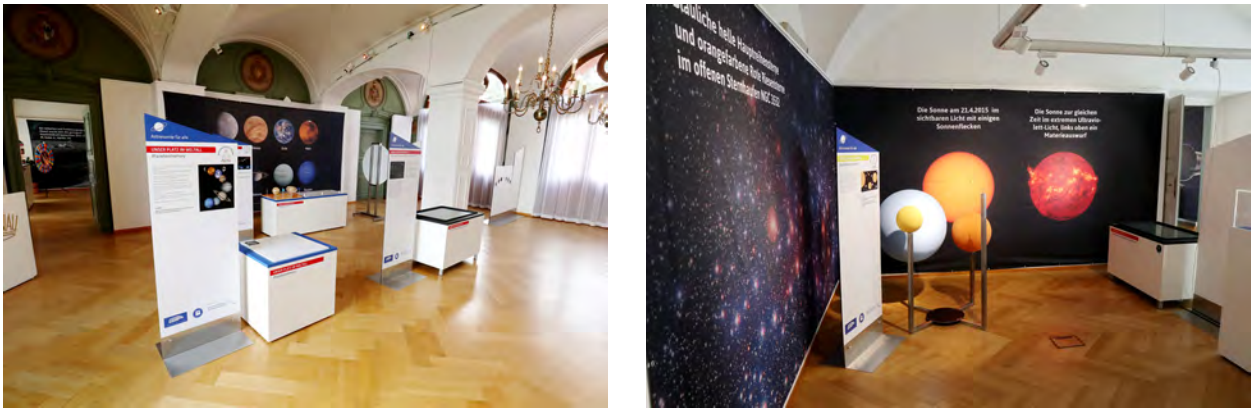
As in previous years, HdA was present with an info booth at the astronomy fair Astro-Messe (AME) in Villingen-Schwenningen. HdA staff also gave around 20 public talks in various locations throughout Germany.

Exhibition Astronomie für Alle

Last year, in collaboration with MPIA and with funding from the Klaus Tschira Foundation, HdA created the exhibition “Astronomie für Alle”, literally “Astronomy for Everybody”. From May 10 to September 22, 2019, the exhibition was featured on Mainau Island, the “isle of flowers” in Lake Constance that is a major tourist attraction in the German South-West. Every year, the island declares an overarching theme, and in 2019, that theme was “Sonne, Mond und Sterne” – “Sun, Moon, and Stars,” the first line of a popular astronomy-themed children's song. Complementing an artisanal scale model of the Solar System, and special presentations of Sun-themed plants, visitors to the island could visit Mainau castle and interact with the exhibits of our astronomy exhibition. The exhibition allows visitors to explore the fundamentals of astronomy, from the Moon to astrophotography, the Solar System and exoplanets, hands-on: Reconstructing the order of the planets of our Solar System, seeing the

Fig. V.3.3: Olaf Fischer explains the apparent motion of the night sky to visitors on Researchers' Night in September 2019.

Credit: C. Liefke / HdA



Credit: M. Pössel / HdA

Credit: M. Pössel / HdA

Fig. V.3.4: Exhibition "Astronomie für Alle" on Mainau Island. Left: Solar-system-themed exhibits in the Heraldic Hall of Mainau castle. Right: Scale models of stars with different sizes.

brightness variations that are at the heart of the so-called transit method of exoplanet detection, or reconstructing a color image of a galaxy from black-and-white images taken through various filters.

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 2019 MPIA Summer Conference on Planetary Dynamics brought more than 70 scientists to HdA from June 3 – 6. Additional conferences this year were "Astronomical Time Series - a workshop on time variable phenomena in astronomy" in January and the JPL/MPIA Workshop in May. In addition, 41 smaller scientific and organizational meetings took place in HdA. All in all, more than 900 scientists and engineers used the HdA as a place for meetings, discussions, and presentations.

Visualization

Spearheaded by our visualisation specialist T. Müller, HdA has undertaken significant activities in the area of visualization – part of our concept from the beginning, but feasible only now that we have a resident expert. Müller's work showcases 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.

For the hundredth anniversary of the 1919 solar eclipse exhibition, produced a four-minute fulldome movie that shows the basics of light deflection in the vicinity of massive bodies, describes the set-up of the 1919 expedition, and visualises both the 1919 results and the more striking scenario of a black hole deflecting light (see Fig. V.3.5).

The movie, called "Checking up on Einstein", was submitted to the 2019 Fulldome Festival in Jena, and is freely available on the ESO fulldome archive. Closer to home, Müller gave a talk about the visual appearance of black hole using our own fulldome planetarium, providing the audience with an immersive virtual journey to the edge of a black hole. He presented a more conventional 2D version as an invited talk at the "Physikalisches Kolloquium" at Hochschule Mannheim.

For HdA's in-house planetarium, Müller has developed a visualization framework for fulldome projection and has supervised a teacher's thesis ("Staatsexamen"; Kiedaisch) with the aim of developing a fully-configurable 3D planetary system simulation for planetaria.

Fig. V.3.5: Still frame from "Checking up on Einstein": Black hole acting as gravitational lens in front of the Milky Way.

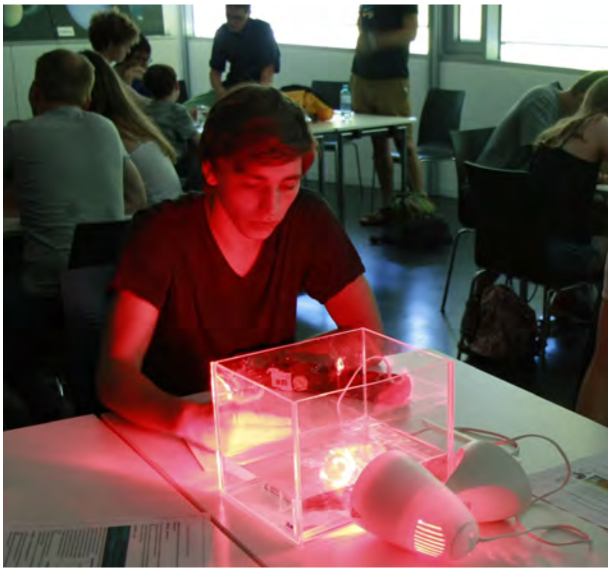
Credit: T. Müller / HdA

In addition to special productions, Müller's expertise regularly benefits numerous of our in-house productions – from special planetarium content for Researchers' night to visualisation support for the “Astronomie für Alle” exhibition. This year also featured astronomy support for two TV productions, one on the polar day and one on the polar night, produced by Marco-Polo Film AG for arte and WDR: two sequences explaining how both phenomena result from the annual movement of the earth around the sun and the tilt of the earth axis. Another collaboration was with the relativistic astrophysics group of the Institute for Theoretical Physics Frankfurt (Rezzolla), which had Müller producing a short movie explaining how the shadow of a black hole emerges and how the distorted view of a thin accretion disk looks like in the run-up of the April 10 press conference presenting the first image of the shadow of a black hole. The video was picked up by a number of media outlets, notably Frankfurter Allgemeine Zeitung.

Visualization work at HdA also has a direct connection to research. Successful collaborations with Heidelberg astronomers included a 3D-Visualization of VLT/MUSE data (Santoro), a short explanatory video for the new nano-calorimetry technique for characterizing the energetics of low-temperature surface reactions (Henning, Krasnokutski), as well as a LIC visualization of the collapse of molecular cloud cores (Bhandare). Müller also continued his work on developing the standalone software Thalia for 2D- and 3D-visualizations of datasets in the context of the THOR project (PI: MPIA's H. Beuther). A cooperation with the Astronomisches Recheninstitut (Sagrista, Jordan) and the Visual Computing Group (Sadlo) at the University of Heidelberg resulted in several technical publications. Together with student assistant Jan Hombeck (Institute for Computational Visualistics, University Koblenz/Landau), and in collaboration with the MPIA's Planet and Star Formation theory group (Klahr), Müller also started to develop a Virtual Reality prototype system to interactively visualize particle data for a better spatial perception of particle distributions. Müller also participated in the (invitation-only) Dagstuhl Seminar (19262) about “Astrographics: Interactive Data-Driven Journeys through Space”.

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.



Credit: C. Liefke / HdA

Fig. V.3.6: Pupils taking part in our hands-on infrared astronomy workshop at Haus der Astronomie.

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 (who has since moved on to 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.

Over the course of the year, more than 3200 pupils and pre-school children visited HdA for a total of 168 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 for primary school students in cooperation with Junge Uni Heidelberg (N. Fischer) and for this year's Explore Science (N. Fischer). For the Researchers Night a turnable star chart was developed (T. Müller, R. Hubele, N. Fischer) and printed

Credit: DLR

Fig. V.3.7: Michaela Doellinger (Landessternwarte Tautenburg) and HdA managing scientist Markus Pössel demonstrate the radial velocity method of exoplanet detection during the DLR_Raumfahrt_Show in Erfurt.

5000 times. In addition 7 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).

External events for pupils included 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). Markus Nielbock served as a jury member of the FIRST Lego League regional elimination contest in Heidelberg.

Arguably the broadest impact this year followed from our collaboration with Germany's space agency DLR, specifically with their "Space Show" on the occasion of the 50th anniversary of the first Moon landing. In his function as IAU National Outreach Coordinator for Germany, Markus Pössel organised the German portion of the IAU's "NameExoWorlds" competition, which allowed countries to give a name to the star and (exo-)planet of a star system. The kick-off of the competition became part of the DLR_Raumfahrt_Show in Steigerwald stadium in Erfurt on June 7, 2019, presented by Pössel and Michaela Döllinger. Döllinger, who is at Tautenburg Observatory, was a co-discoverer of the planet in question, HD 32581b. The main attractions of the show were German astronauts Alexander Gerst and Ulf Merbold. Attended by 15966 school children, the show itself has since been entered into the Guinness World Records data base as the largest Science Show to date. The public poll that decided between the proposed names was won by a physics course from Max-Born-Gymnasium Neckargemünd. The star HD 32581, which is in the constellation Giraffe,

Fig. V.3.8: View of Steigerwald stadium in Erfurt during the DLR_Raumfahrt_Show in June 2019.

Credit: M. Nielbock / HdA

Fig. V.3.9: School children recreating the solar system with luminous planets at the DLR_Raumfahrt_Show in Heidelberg.

now bears the name Mago, after a national park in Ethiopia that is home to a particularly notable population of giraffes. The Neri river is on the border of that national park, and Neri is now the name for the planet HD 32581b.

Later in the year, although on a much smaller scale, a collaboration between HdA, DLR, Heidelberg University and the Forscherstation Heidelberg, with generous funding by the Klaus Tschira Foundation, allowed us to bring the DLR Space Show to Heidelberg. With HdA's Natalie Fischer and Markus Nielbock as moderators, four performances of the show on September 16 and 17 reached a total of 2500 excited school children grades three to six in the main auditorium of Heidelberg University.

Our NameExoWorlds activities were not our only contribution to the anniversary year “100 Years Under One Sky” of the International Astronomical Union: In addition, HdA saw workshops in primary schools in the initiative named Astronomy Day in Schools (N. Fischer, E. Kolar), and we also participated in the Bundesweiter Vorlesetag with reading events for kindergarten groups under a telescope dome (N. Fischer, E. Kolar).

Carolin Liefke gave a workshop on stars at SommerKinderCollege by DHBW Karlsruhe. Together with Dominik Elsässer (TU Dortmund), she also supervised the astronomy course “The Moon” at the Junior-Akademie Baden-Württemberg for gifted high school students in Adelsheim.

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.

Credit: DLR

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). The concept of the course has been presented as a poster at the astroEDU Conference. 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 variable stars to experimental investigation of the fritter effect.

In-service training for teachers 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. V.3.10; O. Fischer), and the one-day course "The Digital Universe – Computers in Astronomy Education" for the Baden-Württemberg education ministry (M. Pössel). For primary school and kindergarten teachers, there were 19 training sessions, six workshop sessions and numerous consultations (N. Fischer). The HdA participated in two congresses in the area of kindergarten and primary school, one with a booth and the other with two teacher trainings (N. Fischer).

External teacher training events 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). At the end of the first course "Cosmic Trilogy" at the State Academy Bad Wildbad a one-week long astronomy internship was carried out on La Palma (O. Fischer, M. Penselin). This year's edition of "Astronomy from Four Perspectives", our German-Italian summer school funded by the WE Heraeus Foundation, took place in Padova. Two teacher training courses for primary school teachers took place in the Pädagogisches Landesinstitut Speyer in the course of the Fachtagung "Begabung entdecken, fördern und entfalten" (N. Fischer).

Our "Telescope Driver's License" workshop, well-established by now, which qualifies teachers for the use of small telescopes in school again took place at the "Rhöniversum" Umweltbildungsstätte Oberelsbach (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). 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-

Fig. V.3.10: Participants of the nationwide teacher training course at Haus der Astronomie in November 2019.

Credit: HdA

Credit: YouTube

Fig. V.3.11: Still frame from YouTube from the tutorial video about setting up a telescope, produced by HdA interns.

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.

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 47 German high school groups participating in four search campaigns (C. Liefke).

LCO has been established as a reliable tool for remote/robotic observations by schools, with real-time remote control restricted to twilight times with the 2m Faulkes telescopes. A number of German schools use the telescopes regularly, including some of the HdA partner schools (C. Liefke). The asteroid recovery project conducted at the Paul-Pfinzig-Gymnasium in Münster based on LCO data and supported by C. Liefke became the second runner-up in the state-wide Nordrhein-Westfalen science competition "Jugend forscht". Within the framework of their Hector Seminar cooperation phase project, two students used LCO archive data to track the passage of comet 46P/Wirtanen and analyse the changes in the orbital parameters of the comet (C. Liefke). In autumn, a new Hector project dedicated to recover near-earth asteroids with the 50cm telescope at HdA/MPIA and the ROTAT remote observatory at Observatoire de Haute Provence in southern France started with two new students. Major issues with the automatic tracking of the dome affected ROTAT in 2019, which were successfully resolved in an extensive maintenance session in July. The telescope has nevertheless been used frequently for near-earth and minor planet discoveries at any time (C. Liefke). High school students at the Astrophysik-AG of Heidelberger Life Science Lab embarked on improving their astrophotography skills using HdA's DSLR camera and star tracker sets (C. Liefke).

Our internship program in 2019 included two one-week "BOGY" and another two-week career orientation weeks, with a total of 21 participants. During the two-week internship, video tutorials for setting up and using our telescopes have been produced, including script-writing, filming, cut and publication on YouTube (C. Liefke, M. Pössel).

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 17 participants from Bangladesh, Canada, Germany, Great Britain, India, Italy, Poland, Sweden, Switzerland, and the USA. Furthermore, we had four 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 trainings for kindergarten and primary school teachers.

HdA also maintains a network of partner schools throughout Germany, encompassing 41 schools in 15 of Germany's 16 federal states; most of them are secondary schools, joind by a local primary school.

Of course, we also collaborate with a number of additional national and international institutions. For instance, there is a fruitful collaboration with Chile. Since 2010, the HdA has been a partner in the DAAD project of the German-Chilean Center of Excellence for Research and Teaching. Since then, 18 two-day teacher training courses on astronomy have taken place at 9 different locations in Chile during 6 stays by HdA employees in Chile. About 1000 Chilean teachers were trained in astronomy education concepts and techniques. Up to now, 15 Chilean teachers have received further, more advanced training during five two-week visits to the House of Astronomy (O. Fischer).

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. This year two teacher trainings, one for primary schools and one for kindergarten took place in the ES (N. Fischer). The HdA also worked with NASE (Network for Astronomy School Education) to develop a workshop on astrobiology. We provided ideas and material for an activity within the workshop, which will be taught as part of the NASE programme (F. Seitz).

Last but not least, throughout 2019, work was ongoing on a new development that will elevate HdA's international networking activities to an all new level: Having submitted a letter of intent for hosting the International Astronomical Union's new Office of Astronomy for Education in late 2018, HdA and MPIA were invited in late February 2019 to submit a full proposal. In mid-September, we received word that our proposal had been selected against a strong field of international competitors. We immediately set in motion preparations of starting up the IAU Office of Astronomy for Education, and presented our plans to participants of the first Shaw-IAU Workshop on Astronomy Education in Paris. That workshop also saw the signing of the MoU between the IAU and MPIA about the foundation of the IAU Office of Astronomy for Education (Fig. V.3.12). We are very excited about entering this new phase of our activities!

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

Fig. V.3.12: Participants of the 1st Shaw-IAU Workshop on Astronoy Education in Paris witness the signing of the founding MoU for the IAU Office of Astronomy for Education. Center group left to right: designated OAE deputy director Carolin Liefke, designated OAE director Markus Pössel, and IAU General Secretary Teresa Lago.

Credit: IAU / A. Gustin

Dossenheim
Handschuhsheim
Ziegelhausen
Wieblingen
Ruprecht-Karls-
Universität
Heidelberg
Neuenheim
Schlierbach
-Ziegelhausen
Heidelberg
Central Station
Eppelheim
Bahnstadt
Pfaffengrund
Königstuhl
Speyrerhof
MPI für
Kernphysik
MPI für
Astronomie
Südstadt
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
Berliner Straße
Steubenstraße
Uferstraße
Neuenheimer Landstraße
Ziegelhäuser Landstraße
In der Neckarhelle
Schlierbacher Landstraße
Am Hackteufel
Burgenstraße
Schumannstraße
Vangerowstraße
Kurfürsten-Anlage
Rohrbacher Straße
Ringstraße
Czernyring
Henkel-Teroson-Straße
Kurpfalzring
Eppelheimer Straße
Speyerer Straße
Römerstraße
Bertha-Benz-Straße
Chaisenweg
Kohlhof Weg
Drei - Eichen-Weg
Gaiberger Weg
A5
E 35
A656
B 3
B 37
B 535
K 4242
K 4243
K 9700
K 9701
K 9702
K 9706
K 9708
K 9710
K 4149
K 4161
L 531
L 534
L 543
L 594
L 598
L 600
L 600a


MAX-PLANCK-GESELLSCHAFT