Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report 2017

Cover Illustration:

1.4GHz continuum image showing free-free and synchrotron emission from the HI/OH/Recombination line survey of the inner Milky Way (THOR). See Chapter II.1, page 24.

Credit: Wang et al. (2018)

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Annual Report

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Max Planck Institute for Astronomy

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Contents

Preface

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

It is in this spirit that the Max Planck Institute for Astronomy pursues its research, with particular focus on galaxies, and on stars with their planets. We develop and build instrumentation, we observe and model data, and we turn that information into insights through theory and computer simulations.

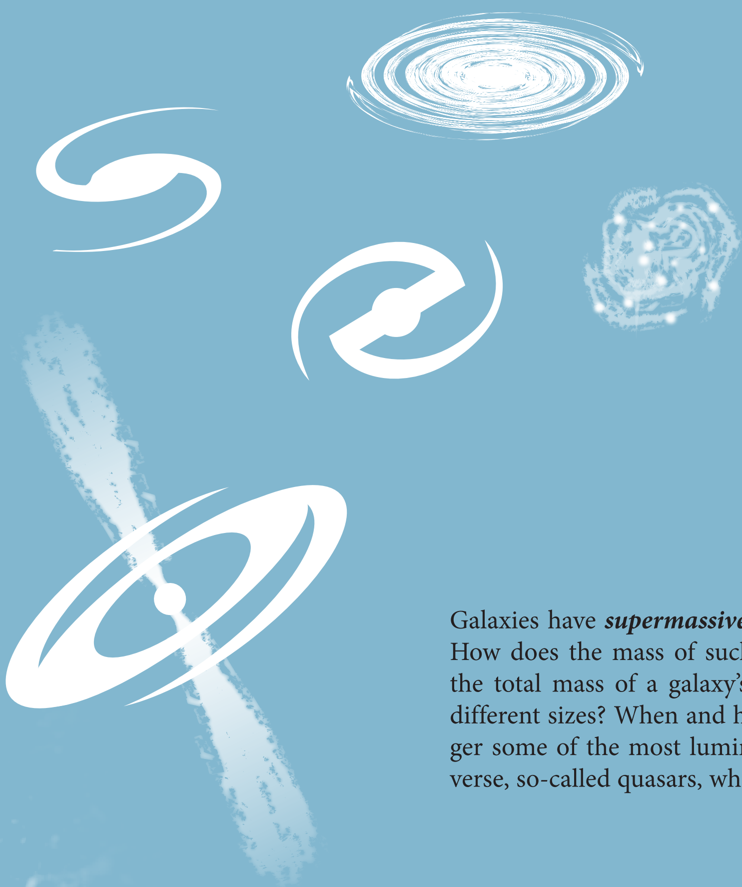
But like all research, our astronomy is people-driven. So, at MPIA we are striving to build and foster an ambitious, enthusiastic and diverse community of excellent researchers, students and engineers. This report provides some snapshots of what we did and what we learned in 2017 about our universe.

Thomas Henning, Hans-Walter Rix

Heidelberg, November 2017

I. MPIA in a Nutshell

Our Fields of Research: Galaxies and Cosmology

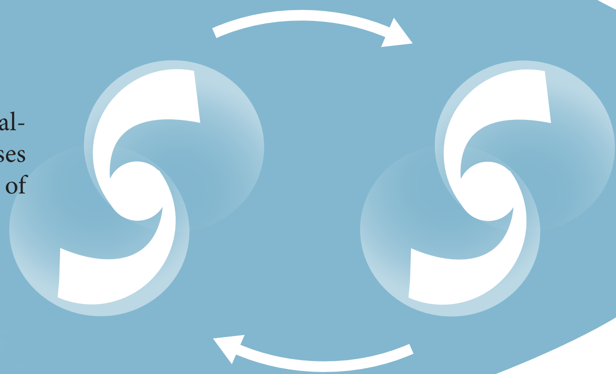


Galaxies come in many shapes and sizes. How do these differences arise? And what factors are responsible for how many stars a galaxy produces?

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

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

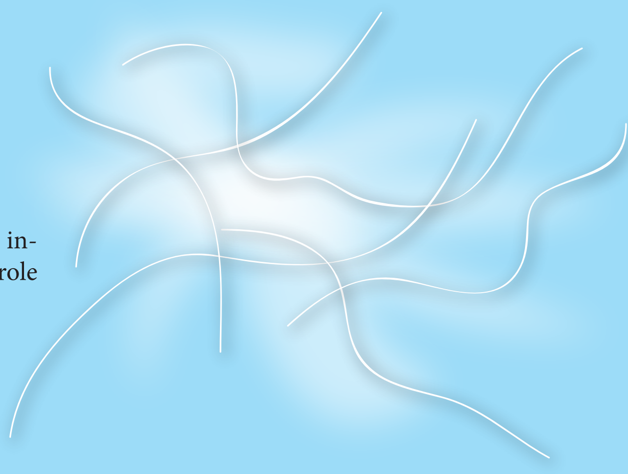
Galaxies grow as they merge with other galaxies or swallow smaller galaxies. How do these growth processes work in detail? How do they influence the properties of different types of galaxies?



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

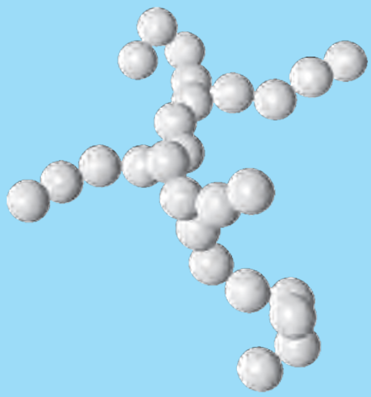
Planet and Star Formation

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



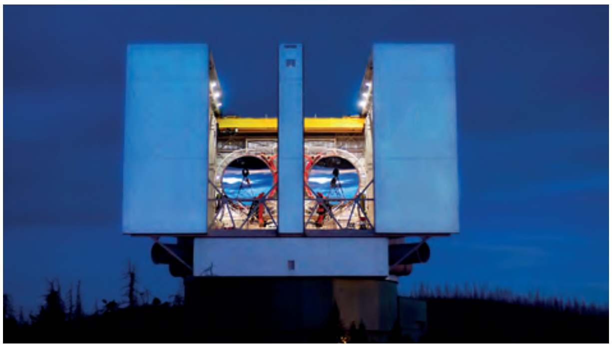
How do ***magnetic fields*** influence which clouds of the interstellar medium collapse to form stars? What is the role of turbulent motions within these clouds?

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

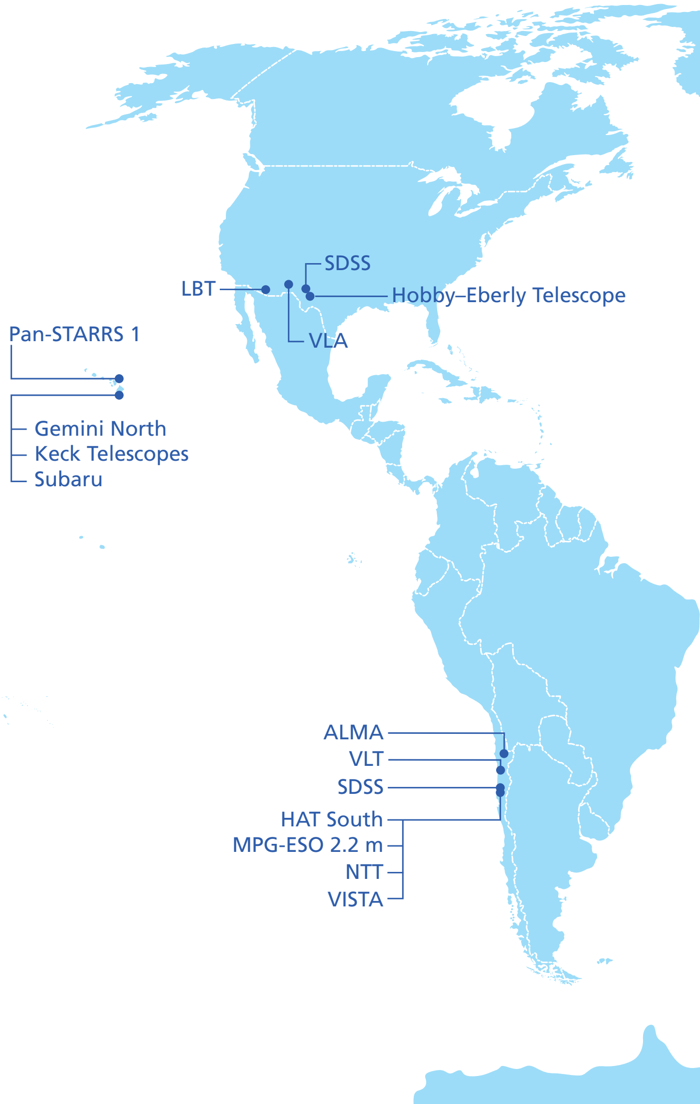


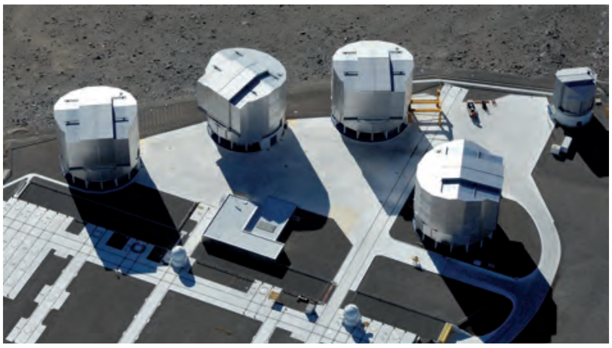
Since 1995, astronomers have discovered more than 3,700 ***exoplanets*** (planets orbiting stars other than the Sun). What can these widely different planetary systems tell us about planet formation?

MPIA Telescopes all Over the World



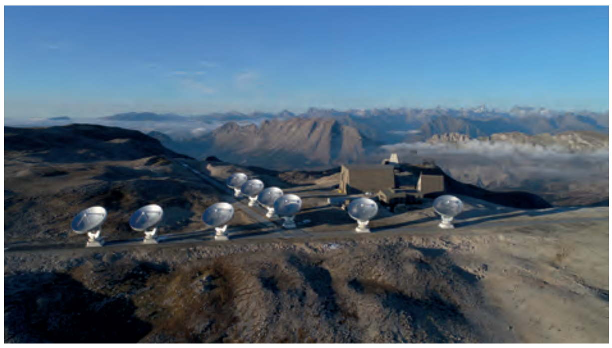
MPIA is part of the consortium operating the Large Binocular Telescope (LBT) on Mount Graham in Arizona. The LBT has two 8.4 meter mirrors on a single mount.



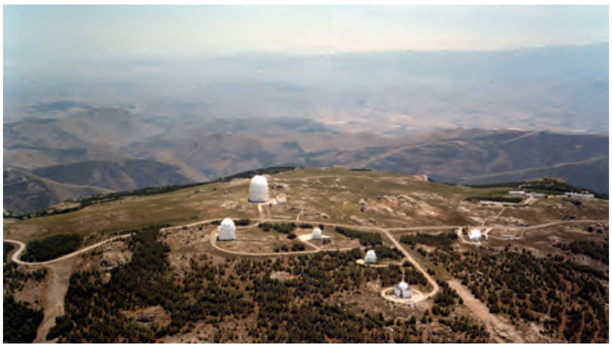


MPIA is involved in the construction of the instruments SPHERE, MATISSE and GRAVITY for ESO's Very Large Telescope at Paranal Observatory.

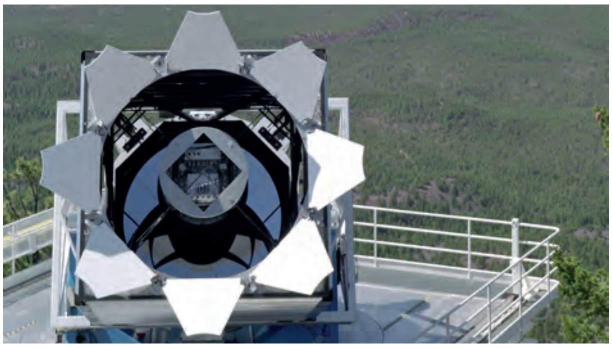
MPIA researchers use the ALMA observatory at Chajnantor in the Atacama Desert to study some of the coldest and most distant objects in the Universe. ALMA is an interferometer for observations in the millimeter and submillimeter wavelength range.



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

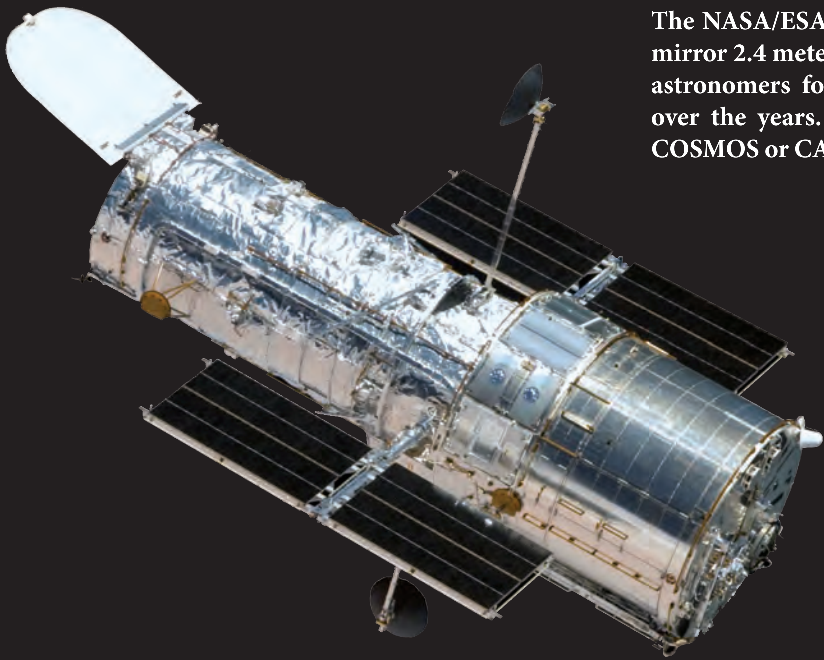


Calar Alto Observatory in Southern Spain was founded in the 1970s by MPIA, and is now operated as a joint German-Spanish research center. In 2016 the CARMENES instrument, in part built by MPIA, began observing at the 3.5 meter telescope.



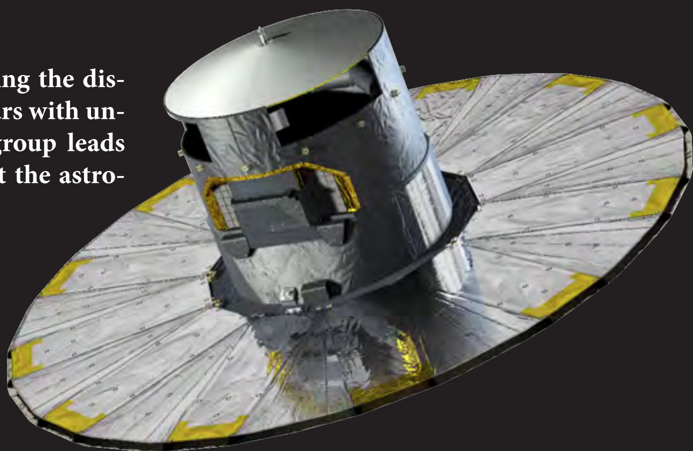
MPIA is a member of the Sloan Digital Sky Survey (SDSS), a spectroscopic survey using a 2.5 meter telescope in New Mexico. The survey gathers high-quality spectra of a large number of astronomical objects.

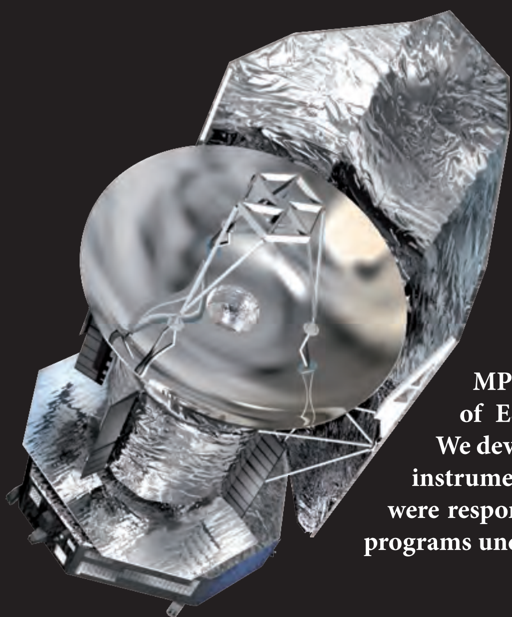
Space Telescopes



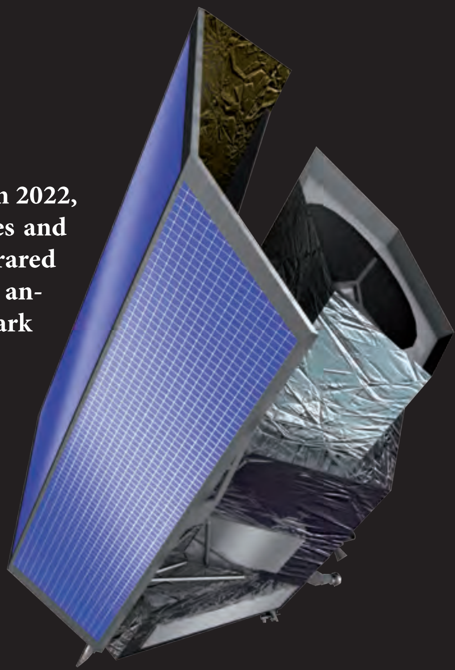
The NASA/ESA Hubble Space Telescope (with a main mirror 2.4 meters in diameter) has been used by MPIA astronomers for a variety of successful observations over the years. This includes larger surveys such as COSMOS or CANDELS that involve MPIA researchers.

ESA's astrometry satellite Gaia is measuring the distance from Earth to more than a billion stars with unprecedented precision. The MPIA Gaia group leads the effort of using this data to reconstruct the astrophysical properties of those stars.

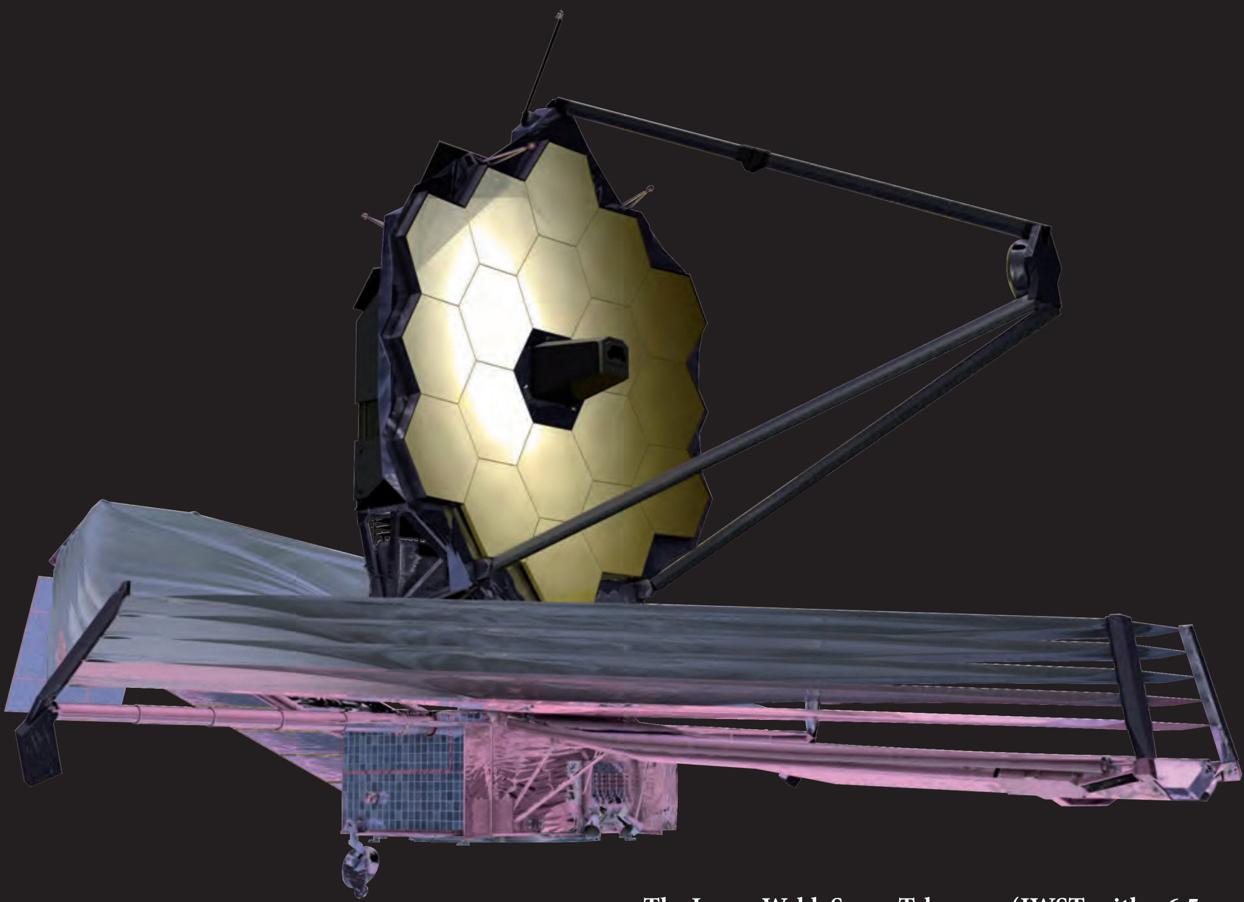




MPIA contributed to the construction of ESA's infrared observatory Herschel: We developed key components for the PACS instrument aboard the Herschel satellite, and were responsible for a number of observational programs undertaken with Herschel.



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



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

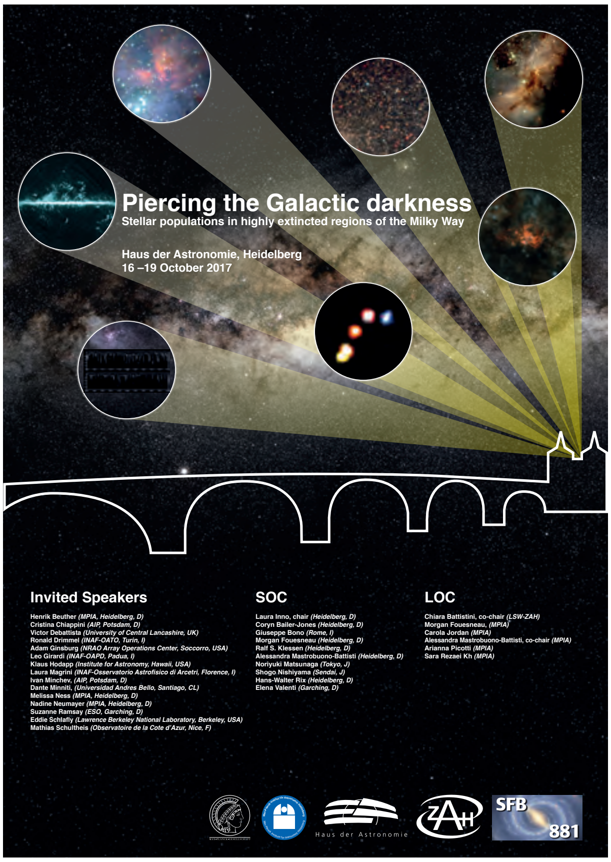
Major conferences organized by our staff members

The exciting lives of galactic nuclei (Ringberg Meeting)
27 February – 3 March
Ringberg Castle, Tegernsee

Galactic Star Formation with Surveys (6th MPIA Summer Conference)
3 – 7 July
Haus der Astronomie, Heidelberg

Piercing the Galactic Darkness
16 – 19 October
Haus der Astronomie, Heidelberg

Galaxy Evolution in Groups and Clusters at 'low' Redshift: Theory and Observations
11 – 15 December
Ringberg Castle, Tegernsee



Bottom: Participants of the conference "Galaxy Evolution in Groups and Clusters at 'low' Redshift: Theory and Observations", co-organized by MPIA's Annalisa Pillepich, in Ringberg. *Right:* Poster of the conference "Piercing the Galactic darkness" at Haus der Astronomie, Heidelberg.

Credit: A. Pillepich (MPIA)

Awards and Prizes

André Müller

Nadine Neumayer

DFG Research Grant

André Müller
Research funding from the German Research Foundation (DFG) as part of the 1992 priority programme "Exploring the Diversity of Extrasolar Planets".

Schiemann Fellowship, Tinsley Scholarship

Nadine Neumayer
Elected member of the Elisabeth Schiemann College of the Max Planck Society; Beatrice M. Tinsley Visiting Scholar, The University of Texas at Austin.

Patzer Prizes 2017

Anna-Christina Eilers, MPIA
for her publication "Implications of $z \sim 6$ Quasar Proximity Zones for the Epoch of Reionization and Quasar Lifetimes" (2017, Astrophysical Journal, 820, 24).

Daniel Rahner, ZAH/ITA
for his publication "Winds and radiation in unison: a new semi-analytic feedback model for cloud dissolution" (2017, Monthly Notices of the Royal Astronomical Society, 470, 4453)

Marta Reina-Campos, ZAH/ARI
for her publication "A unified model for the maximum mass scales of molecular clouds, stellar clusters and high-redshift clumps" (2017, Monthly Notices of the Royal Astronomical Society, 469, 1282)

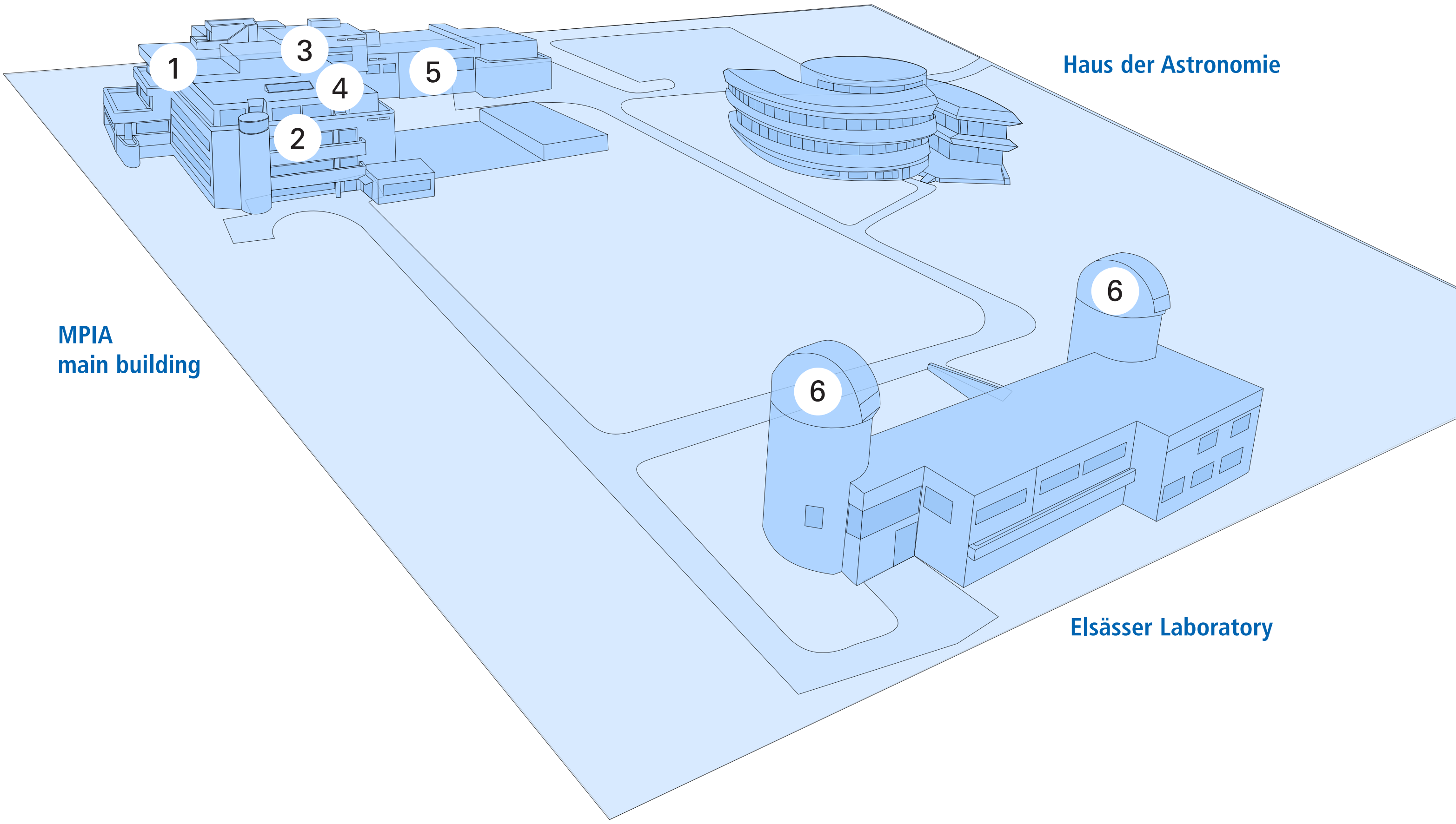
Patzer Prize Winners 2017 (*from left to right*): Marta Reina-Campos, Anna-Christina Eilers and Daniel Rahner

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.

Workshops and construction facilities, here the infrared instrumentation workshop.



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

Experimental and assembly facilities including clean rooms for instrumentation.

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

312

employees
keep the institute running. 215 of these are scientists, including 67 junior scientists or long-term visitors and 64 PhD students.

3,360

cores
are at the heart of MPIA's new ISAAC supercomputer, installed in February 2017 at the Max Planck Computing & Data Facility in Garching.

6

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

55 million

core hours
were used by MPIA researchers on the Max Planck Society's supercomputers HYDRA and DRACO, corresponding to 6% of these powerful machines' total capacity.

342

articles
were published by MPIA researchers in peer-reviewed journals in 2017.

13 billion

years
is the time it took light from the most distant known quasar, discovered in 2017 as part of a search led by MPIA researchers to reach Earth.

MPIA in Numbers

II. Research: Departments, Collaborations, Highlights

Credit: The Illustris Collaboration

II.1 Departments

Planet and Star Formation – The PSF Department

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 finally provide the necessary conditions for the origins of life on planets which are located in their habitable zones.

Stars are born in the densest and coldest parts of molecular clouds – giant molecular hydrogen clouds enriched with dust particles and a large variaty of chemical specres with masses many thousands of times that of the Sun. As parts of these clouds collapse under their own gravity, some compact regions become sufficiently hot and dense for nuclear fusion to set in: a star is born. The formation of planetary systems is a natural by-product of low-mass star formation. It takes place in protoplanetary disks of gas and dust which surround the nascent stars. Our own Solar System came into being in this manner some 4.5 billion years ago.

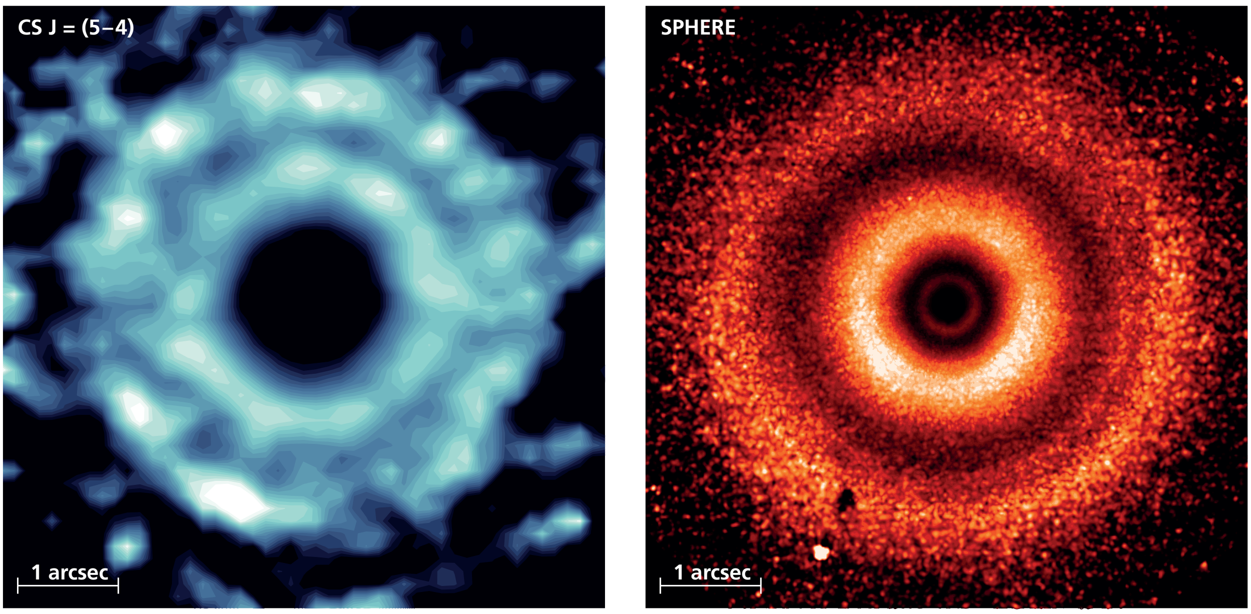
Scientists in the PSF department attack a broad range of open questions related to the process of star and planet formation, combining multi-wavelength observations with large-scale numerical simulations and dedicated laboratory experiments.

Observing the formation of stars and planets first-hand

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

PSF researchers use a comprehensive set of telescopes and facilities for their work, including the Hubble Space Telescope and ground-based facilities such as ESO's Very Large Telescope, the Large Binocular Telescope in Arizona, NOEMA (NOrthern Extended Millimeter Array), the Atacama Large Millimeter/Submillimeter Array ALMA, and the Karl G. Jansky Very Large Array. Scientists of the department are actively involved in the preparation of science with the James Webb Space Telescope, which is scheduled for launch in 2021. Observations with these telescopes provide insights into the physics and chemistry of the interstellar medium and the earliest stages of star and planet formation and allows MPIA scientists to diskover and characterize exoplanets.

Fig. II.2.1: The protoplanetary disk around the young star TW Hydrae. Left image uses light from a spectral line of carbon monosulfide (CS), right image light scattered by dust particles in the disk. Some of the characteristic ring structures are visible in both images.



Credit: *Left* R. Teague (MPIA), ALMA (ESO/NAOJ/NRAO). *Right* R. van Boekel (MPIA), ESO

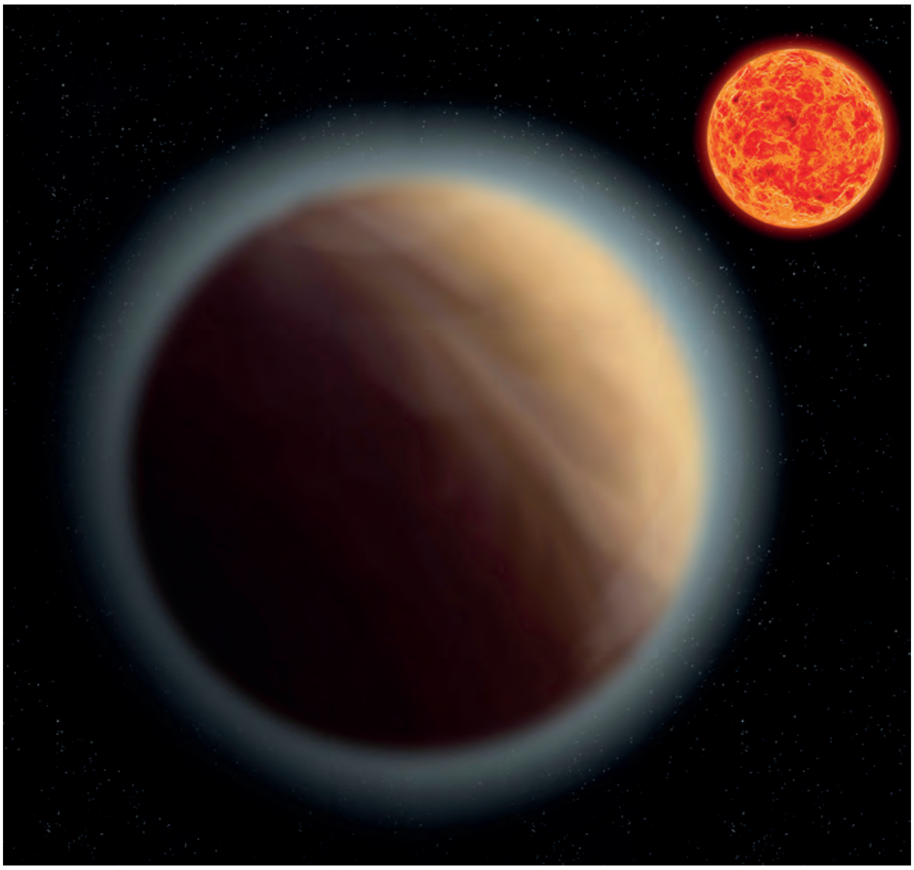


Fig. II.1.2: Artist's impression of the exoplanet GJ 1132 b, which orbits the red dwarf star GJ 1132. Astronomers have managed to detect the atmosphere of this Earth-like planet.

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

The PSF department is involved in several programs that rise to this considerable challenge: adaptive optics is a technique to compensate for the distortions of astronomical images by Earth's atmosphere, allowing large telescopes to reach particularly high resolution. Interferometry 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, and 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? More specifically: How does the probability for the formation of a star of a given mass depend on the mass of the star-forming cloud?

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

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

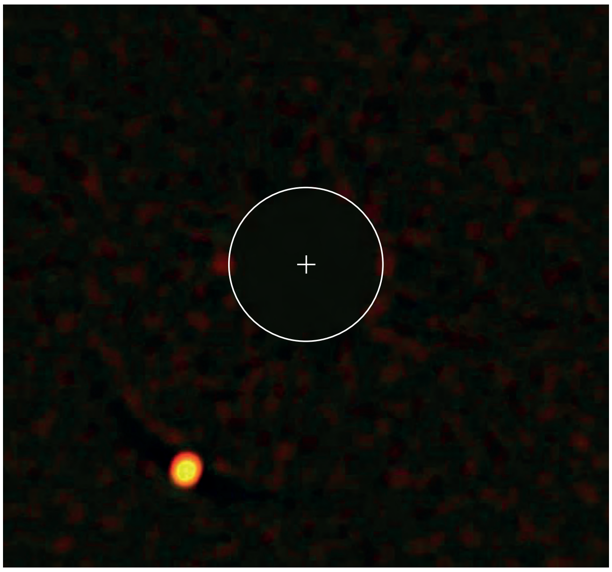
How do molecular clouds form from clouds of atomic hydrogen? What regulates the onset of star formation and the star formation efficiency? What triggers the fragmentation of molecular clouds? What is the role of filamentary structures in the star formation process? What is the mass limit for the highest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

A peek behind the curtain

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

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

While the protostar still accretes matter from the surrounding disk, some of the matter is ejected perpendicular to the disk in the form of molecular outflows, or as collimated, ionized, high-velocity jets. Direct observations of such disks and the associated accretion and outflow phenomena can provide insights into both the formation of our own Solar System and the diversity of planetary systems in general.



Credit: G. Chauvin et al. / SPHERE

Fig. II.1.3: Image of the planet HIP 65426 b (*bottom left*), produced with the SPHERE instrument. SPHERE has physically blocked out light from the central star (*blocked-out region marked by circle*) in order for the planet's much weaker light to become detectable. The light received from the planet allows deductions about its properties – in this case the presence of water vapor and reddish clouds.

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 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 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 of the department have established large observing programs at internationally competitive astronomical facilities.

Presently, the department is strongly involved in the preparation of projects in the field of star formation and protoplanetary disks for the James Webb Space Telescope (JWST), the designated successor to the Hubble Space Telescope scheduled for launch in 2021. As a member of the consortium for the JWST mid-infrared instrument MIRI, we have access to guaranteed time for this instrument.

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

Planet formation and the search for exoplanets

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

PSF astronomers are heavily involved in observing programs to search for extrasolar planets through direct imaging, the transit technique and radial velocity observations of objects diskovered with the Kepler Space Telescope. The HATSouth transit network, with its three stations in Australia, Chile, and Namibia, is currently returning a flood of new diskoveries, and the K2 mission extension of the Kepler observatory is allowing us to detect super-Earths around relatively bright stars. The new CARMENES spectrograph at the Calar Alto Observatory is one of the most versatile instruments to search for exoplanets around M-type stars. A multi-year survey has just started to unravel the statistics of low-mass planets around these red stars, and the first planet diskoveries could be made.

The consortium of the SPHERE planet finder instrument, where MPIA is the Co-PI institute, is presently embarking on 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 to rings and spiral arms, which point to complex dynamics and planet-disk interactions. The department is a core member of the LBT LEECH planet search program and has initiated a large survey for young planets with the adaptive-optics instrument NACO.

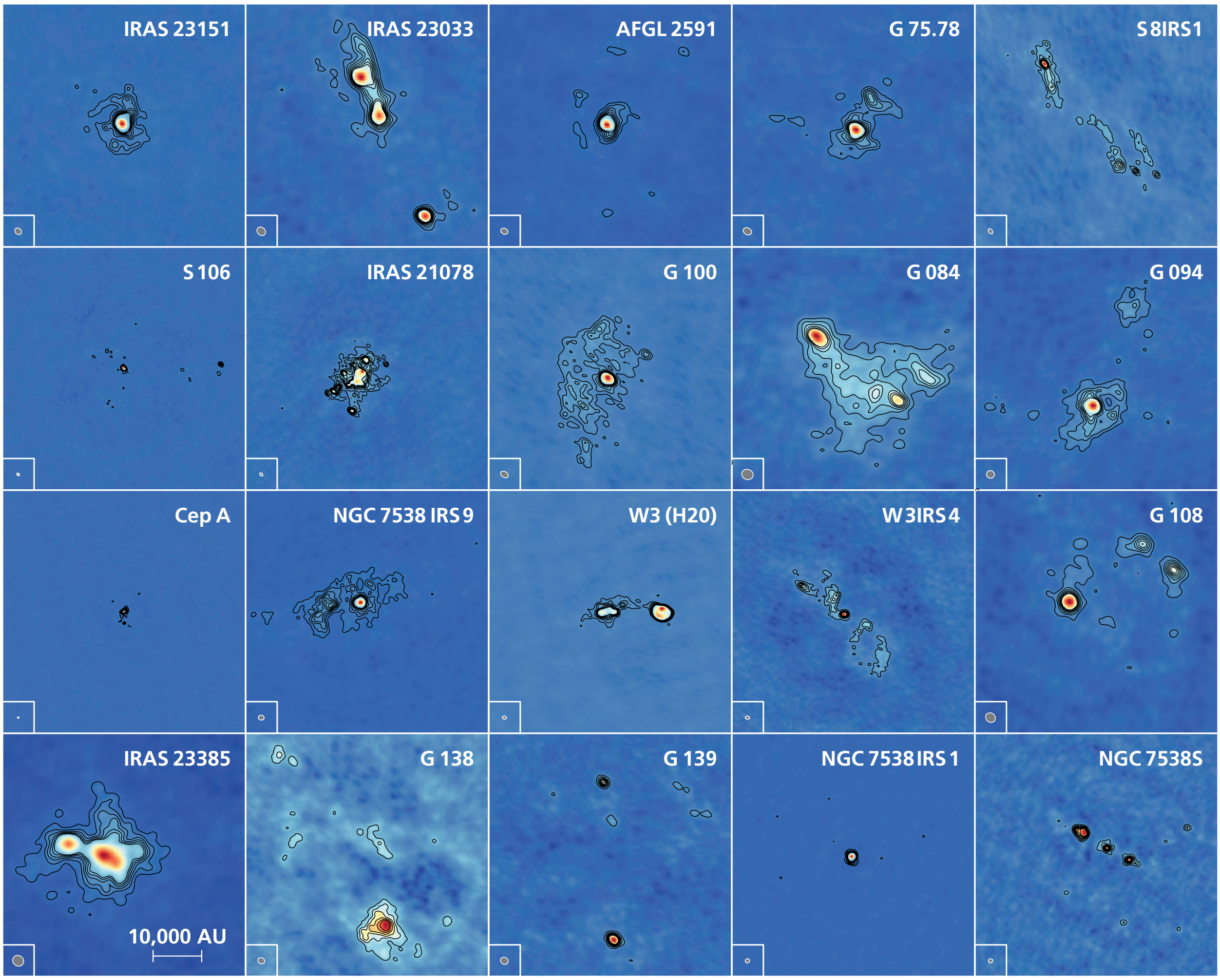
In addition, two instruments for ESO's Very Large Telescope Interferometer with strong technical and scientific involvement of the PSF department, GRAVITY and MATISSE, are in their final stage of construction. GRAVITY has already seen first light and is starting to produce amazing scientific results. These instruments will allow us to study the cradles of planets – the protoplanetary disks – with unprecedented spatial resolution, complementing our observations with the IRAM and ALMA (sub)millimeter interferometers.

Star and planet formation in a computer

A deep 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. Additional topics of our theory group are the formation of massive stars and star formation on galactic scales.

The theory group of the PSF department is developing multi-dimensional radiative transfer codes which simulate the way radiation travels through molecular clouds and their cores, protoplanetary disks, and the atmospheres of planets. These codes can be used for interpreting cloud and disk images and spectra, and they also allow researchers to employ magneto-hydrodynamic simulations and reconstruct how the object in question would look to observers. Another important application is to 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.

Fig. II.1.4: 1.3 mm continuum images taken regions with NOEMA of a sample of twenty high-mass star formation. The image shows how the dust and gas of these regions fragments. From these fragments, separate stars with different masses will form within the next million years.



Credit: H. Beuther et al. 2017/2018

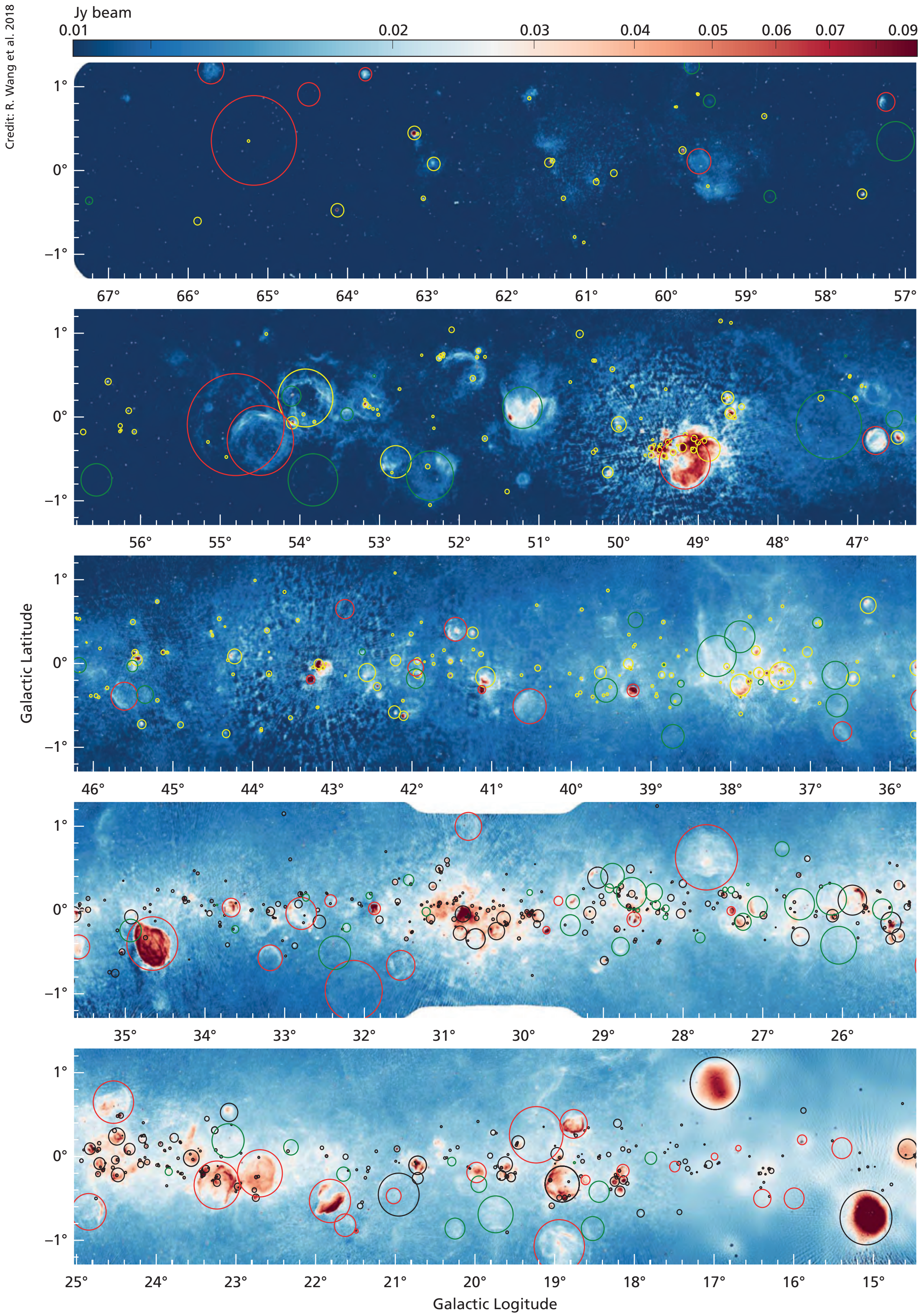

Credit: R. Wang et al. 2018
Jy beam
0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.09
1° 0° −1°
67° 66° 65° 64° 63° 62° 61° 60° 59° 58° 57°
56° 55° 54° 53° 52° 51° 50° 49° 48° 47°
46° 45° 44° 43° 42° 41° 40° 39° 38° 37° 36°
35° 34° 33° 32° 31° 30° 29° 28° 27° 26°
25° 24° 23° 22° 21° 20° 19° 18° 17° 16° 15°
Galactic Latitude
Galactic Logitude

Fig. II.1.5: Centimeter continuum map of a large area of our Milky Way obtained with the THOR (The HI/IOH/Recombination line survey of the Milky Way) survey by Wang et al. The yellow circles mark HII regions whereas the red and green circles outline Supernovae and Supernova candidates.

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 group investigates the spectroscopic properties of nano- and micron-sized solid particles, as well as of complex molecules, especially polycyclic aromatic hydrocarbons (PAHs), an important class of organic molecules found in astronomical settings in the gas phase. The scientists of the astrophysics laboratory group also study the formation pathways of small particles and their interaction with molecular ice layers.

Linking the cosmos with laboratories of another kind altogether, namely those of our colleagues in macromolecular chemistry, biogeochemistry and the life sciences, is the aim of another initiative: the Heidelberg Origins of Life Initiative (HIFOL) recently established by the PSF department in collaboration with other scientific institutes in Heidelberg. The goal of this initiative is to understand the basic physical, chemical and biological processes involved in the origins of life, and to connect them with the astrophysical conditions important for the emergence of life.

II.2 Departments

Galaxies in their Cosmological Context – The GC Department

How the Universe became interesting

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

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

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

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

Fig. II.2.1: The galaxy NGC 6946. In the background: an image in regular light (optical). Superimposed in red (false color): radio emission in the 3 cm band, which indicates regions of star formation.

Credit: Red Foreground: F. Tabatabaei/KINGFISHER Team,
Background: NASA, ESA, STScI, R. Gendler, and the Subaru Telescope (NAOJ)

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

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

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

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

Gas: the fuel for making the stars in galaxies

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

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

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

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 which can be addressed using current tools and methods.

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

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

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

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

From observations to simulations

In order to tackle these questions, the GC department follows a three-pronged approach. On the one hand, we study galaxies in the present-day Universe, including our own Milky Way, making the most of the level of detail afforded by observations in our direct cosmic neighborhood.

On the other hand, we study galaxies at earlier cosmic epochs directly by observing very distant objects (corresponding to high cosmological redshifts z); after all, astronomy always means observing the past: when light from a distant galaxy takes, say, 9 billion years to reach us, our present observations show us that galaxy as it was 9 billion years ago, affording us a glimpse into the distant past.

Finally, we compare our observations with physical models. 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. Comprehensive studies of galaxy evolution also require observations across the whole of the electromagnetic spectrum from X-rays to radio wavelengths.

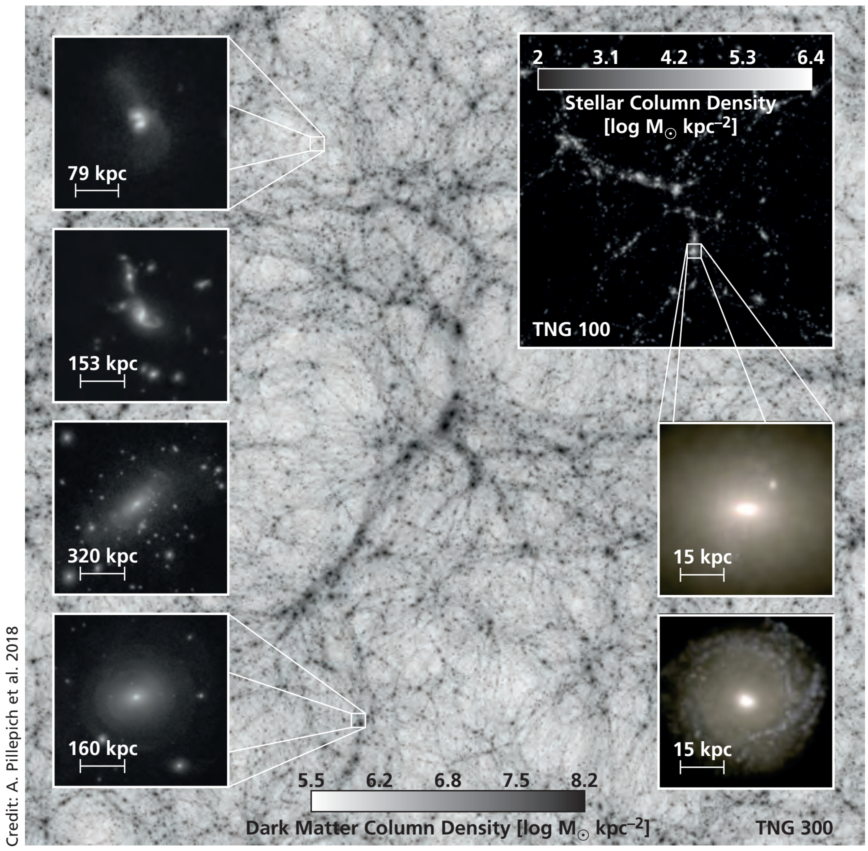


Fig. II.2.2: The IllustrisTNG Simulations: $z = 0$ visual representation of the scope and spatial volumes encompassed by the TNG 100 and TNG 300 runs. The background represents the DM density field across the ~300 Mpc volume of TNG 300, while the upper right inset shows the distribution of stellar mass across the entire ~100 Mpc volume of TNG 100, each projected through a slice a third of the box in depth. Panels on the left show two examples of galaxy-galaxy interactions, and two examples of fine-grained structure of the extended stellar haloes – shells, tidal tails, and luminous satellites – around two massive ellipticals at $z = 0$, in projected stellar mass density. The bottom right insets show the stellar light on scales of 60 kpc per side (face-on) of two randomly-selected $z = 0$ galaxies with a stellar mass larger than $10^{11} M_\odot$, from the high-resolution TNG100 box.

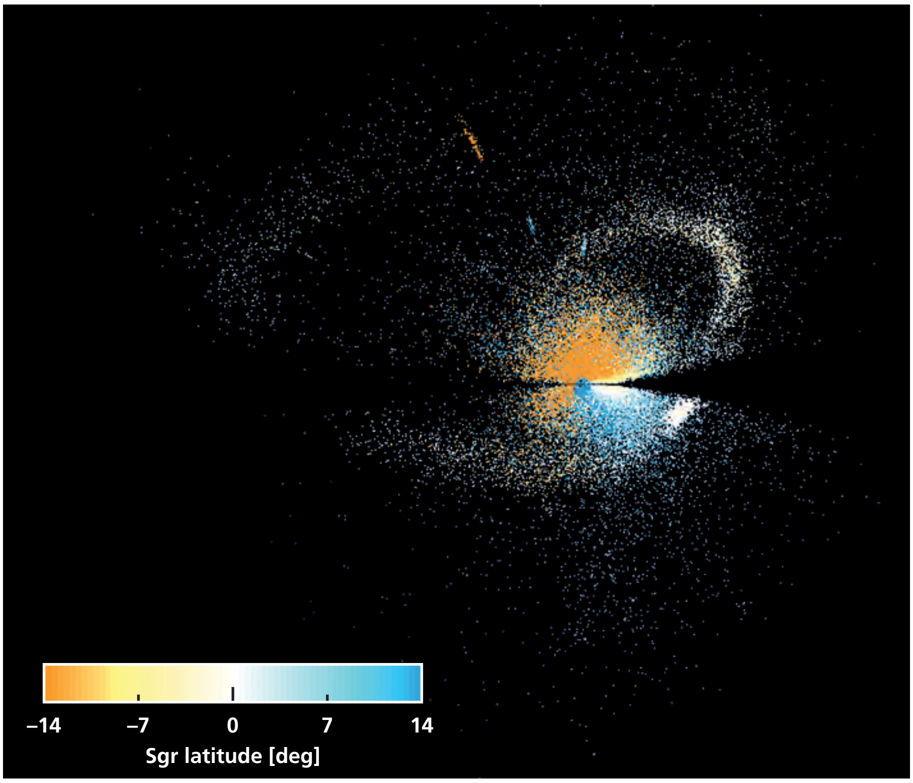


Fig. II.2.3: 3D distribution of about 44,000 RR Lyrae variable stars of subtype RRab, selected by Branimir Sesar and colleagues from the Pan-STARRS 1 3 π survey. Colors indicate distance above or below the orbital plane of the Sagittarius stream. The arcs of the Sagittarius stream are clearly visible in white. The extended overdensities are dwarf spheroidal galaxies such as Draco, Sextans and Ursa Minor.

Collaborations and initiatives

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

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

MPIA has had a leading role in making 3D maps of the Milky Way with the PS1 survey and with Gaia, and is playing a key role in delivering Gaia's first revolutionary data release, scheduled for April 2018. Finally, MPIA is leading the near-infrared photometry effort on ESA's Euclid mission, which will elucidate the most puzzling aspects of physics in the cosmos: the nature of dark energy.

II.3 International 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.

PanSTARRS 1 Sky Survey

The PS1 Science Consortium funds the operation of the Pan-STARRS1 telescope on Mount Haleakala in Hawaii. The telescope features the largest digital camera in the world. During the PS1 survey, the telescope made repeated scans of the sky in order to provide timeseries data of astronomical phenomena – a "movie" of the night sky, ideal for discovering transient phenomena. The consortium consists of astronomers from 10 institutions from four countries, including MPIA. The data taking for the survey is now finished, and the data were released to the scientific community in late 2016, but the scientific analysis continued in 2017.

Sloan Digital Sky Survey IV and V

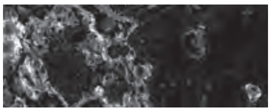
MPIA is a member of the Sloan Digital Sky Survey IV (SDSS), a spectroscopic survey using the Sloan Foundation 2.5 meter telescope at Apache Point Observatory. Previous SDSS have revolutionized astronomy, providing quality spectroscopic data in unprecedented amounts and enabling statistical analyses that previously would have been impossible.

After 20 years of the Sloan Digital Sky Survey, the concept of spectroscopic sky surveying will be taken to a new level, all-sky, multi-epoch spectroscopy of stars and black holes, in the context of the SDSS-V project. MPIA is playing a central role in this project, as a full institutional partner and by providing the Project Scientist and a Survey Scientist, in the extensive international consortium. SDSS-V will require an extensive hardware upgrade on the two (SDSS IV) observatories in both hemispheres, Apache Point Observatory and Las Campanas. Supported by a large grant from the Sloan Foundation, the survey aims to begin in 2020.

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.

IllustrisTNG: taking galaxy formation simulations to the next level



The IllustrisTNG project is an ongoing series of large, cosmological magnetohydrodynamical simulations of galaxy formation, to illuminate the physical processes that drive galaxy formation. The simulations, a close collaboration between HITS, MPIA and an international consortium, use a state of the art numerical code which includes a comprehensive physical model and runs on some of the largest supercomputers in the world. TNG is a successor to the original Illustris simulation and builds on several years of effort by many people.

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 the Max Planck Institute for Astronomy, the Max Planck Institute for Nuclear Physics, the Heidelberg Institute for Theoretical Studies, and the University of Heidelberg in order to further our understanding of the origins of life in the Universe.

DFG Priority Programs

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

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 on the Southern hemisphere to search for transiting exoplanets. The telescopes are located in Namibia, Australia, and Chile. By now, the survey has 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.

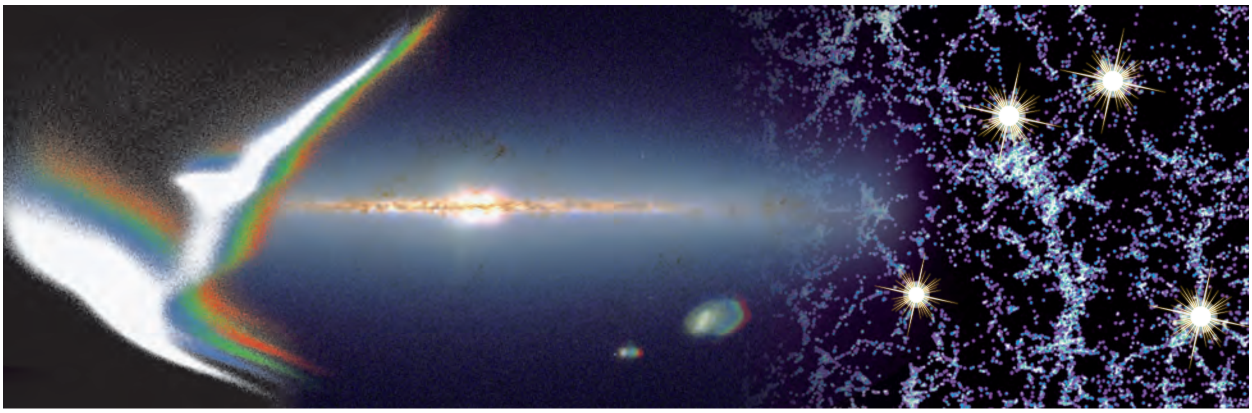
THOR – The HI, OH, Recombination Line Survey

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.

Additional initiatives with active MPIA involvement are the technological collaboration Frontiers of Interferometry in Germany FrInGe, the Opticon network for institutes involved in planning and building optical and infrared instruments and telescopes, the international consortium Chemistry in Disks (CID) focusing on the chemistry and physics of protoplanetary disks and the exoplanet search LEECH at the Large Binocular Telescope. In October 2015, MPIA signed a collaboration agreement with the Institute for Physics and Astronomy (IFA) of the Universidad de Valparaíso, Chile, to set up the first Max Planck Tandem Group in the field of Astronomy in Chile. This new research group at IFA is now in full operation and closely associated with MPIA.

The PSF Department is continuing to organize the annual Harvard-Heidelberg star formation meetings and biannual Tokyo-Heidelberg meetings on planet formation, bringing together key players in these fields of research.

Fig. II.3.1: Symbolic rendition of the main areas of research for SDSS-V, from left to right: mapping the properties of stars, of our home galaxy, and of the large-scale structure of the universe.



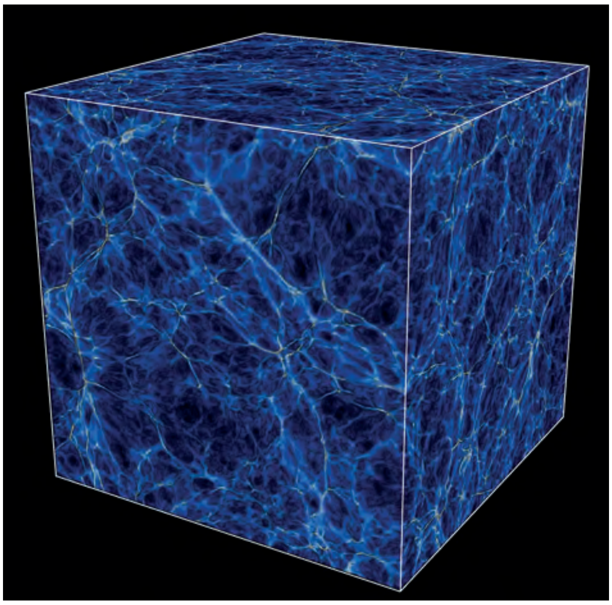
Credit: SDSS

II.4 Highlight

Ripples in Cosmic Web Measured Using Rare Double Quasars

Astronomers believe that matter in intergalactic space is distributed in a vast network of interconnected filamentary structures known as the cosmic web. Nearly all the atoms in the Universe reside in this web, vestigial material left over from the Big Bang. A team led by researchers from the Max Planck Institute for Astronomy have made the first measurements of small-scale fluctuations in the cosmic web just 2 billion years after the Big Bang. These measurements were enabled by a novel technique using pairs of quasars to probe the cosmic web along adjacent, closely separated lines of sight. They promise to help astronomers reconstruct an early chapter of cosmic history known as the epoch of reionization. The results were published in the April 28 edition of the journal Science.

On the largest scales, hundreds of millions of light-years and beyond, the dominant structure in the Universe is the cosmic web: a network of intersecting filaments that consist mostly of dark matter, some of them spanning billions of light years. Dotted along these filaments, each within its own halo of dark matter, are galaxies, like our own Milky Way, from dwarf galaxies to the largest galaxies more than 100,000 light-years across. Typically, the most massive galaxy clusters are found at the nodes of the web, where filaments intersect.



Credit: J. Onorbe / MPIA

Galaxies, however, account for only a tiny fraction of the web's volume. Most of the volume is made up of intergalactic space. In these vast expanses between the galaxies there are neither stars nor planets. The only matter present is in the form of solitary atoms: a diffuse haze of hydrogen gas left over from the Big Bang, on average one per cubic meter in total, and a few per cubic meter within the filaments of the cosmic web. If the galaxies are the decorative dots along the filaments, this hydrogen is a diffuse haze, tracing the dark matter distribution throughout the cosmic web.

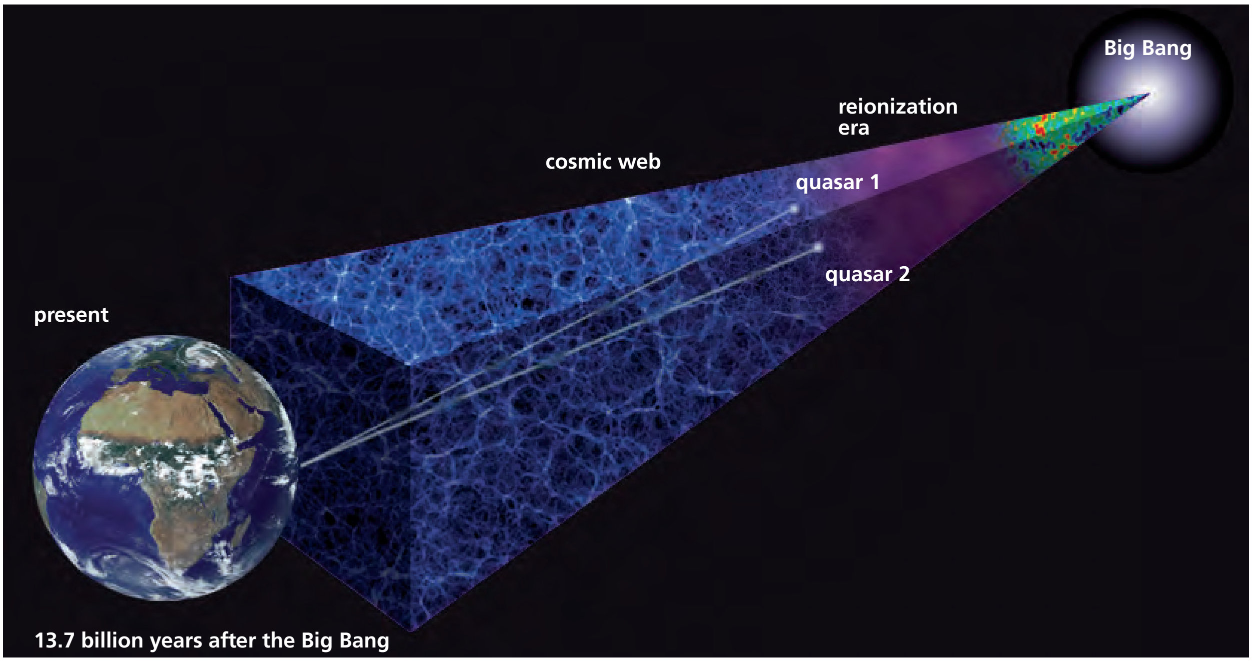
An evolving network of filaments

The evolution of this cosmic web is one of the central issues of cosmic history, and is described by complex cosmological simulations. Current models assume that this large-scale structure grew out of tiny fluctuations in the density of material just after the Big Bang, 13.8 billion years ago. Our earliest picture of the Universe comes from the cosmic background radiation: the thermal radiation that was set free after the Universe became transparent, when the initial plasma had condensed to form (mostly hydrogen) atoms. The inhomogeneities within the cosmic background radiation are the seeds of the large-scale cosmic structure, corresponding to regions of slightly more or less than average density.

Simulations like the Millennium simulation and its kin can reproduce how these initial inhomogeneities evolved into the large-scale filamentary structure we see today, 13.8 billion years later: regions of higher density having slightly stronger gravitational attraction, and thus increasing their density ever further; asymmetries leading to the contraction of inhomogeneous regions into slender filaments, forming the cosmic web. This scenario forms the backbone of the current models of cosmic evolution; the search for an understanding of how galaxies formed and evolved in this framework is a central question of modern cosmological research.

Fig. II.4.1: Volume rendering of the output from a supercomputer simulation showing part of the cosmic web, 11.5 billion years ago. This and other models of the Universe were generated and directly compared with quasar pair data in order to measure the small-scale ripples in the cosmic web. The cube is 24 million light-years on a side.

Credit: Springel et al. (2005) (cosmic web) / MPIA graphics department



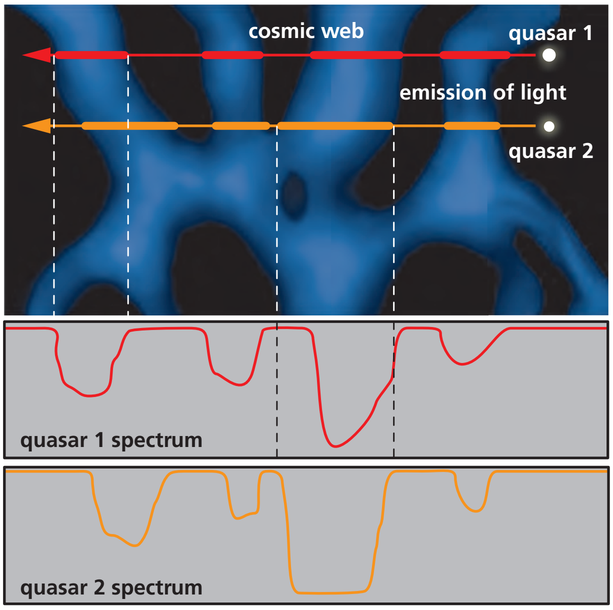


Fig. II.4.2: Schematic representation of the technique used to probe the small-scale structure of the cosmic web using light from a rare quasar pair. The spectra (*bottom right*) contain information about the hydrogen gas the light has encountered, as well as the distance of that gas.

All the more important are tests of the currently accepted models of the evolution of the cosmic web. But when it comes to observing the cosmic web, astronomers face a fundamental difficulty. Dark matter is, by definition, dark. But even the intergalactic gas is so rarified, its density so small, that it emits no measurable amounts of light.

Tracing the web: quasars as intergalactic beacons

Fortunately, there is a specific observational technique that can detect the elusive intergalactic medium. The observations in question target not light emitted by the hydrogen gas, but light emitted by a source that is farther away from us than the hydrogen, and whose light is then partially absorbed by the gas. The light sources in question are known as quasars: a brief hyper-luminous phase of the galactic life-cycle, powered by the infall of matter onto a galaxy's central supermassive black hole. Quasars are very bright indeed – a single quasar can be as bright as all the hundreds of billions of stars in a galaxy put together. This means that quasars are visible over extremely large distances. The most distant known quasars are so far away that their light has travelled nearly 13 billion years to reach us.

Compared with galaxies, the light-emitting regions of quasars are very small; as far as we are concerned, they may as well be point-like. By analyzing quasar spectra, it is possible to deduce both the amount and the distance of intergalactic hydrogen gas the quasar light has encoun-

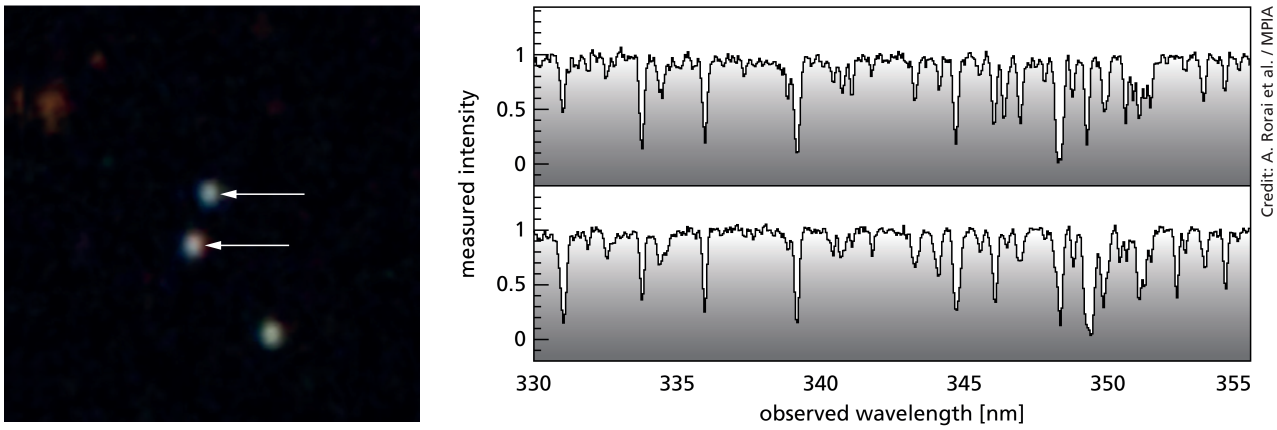


Fig. II.4.3: Spectra of both members of a close quasar pair used in the study. The subtle differences in the absorption features between the two lines of sight allow the researchers to probe the small-scale structure of the cosmic web.

tered on its way. Light is absorbed by hydrogen atoms at specific wavelengths. In the spectrum, the rainbow-like decomposition of light, this absorption is visible in the shape of sharply defined, dark lines, known as absorption lines. The more hydrogen the light encounters, the deeper and more pronounced the absorption lines. As a consequence of cosmic expansion – galaxies in the Universe all moving away from each other on large scales –, light from distant objects such as our quasar is shifted towards longer wavelength in what is known as the cosmological redshift.

Depending on how far the quasar light has already travelled before it encounters intergalactic hydrogen gas, it has already been redshifted by a certain amount. The redshift is related directly to how far light has already travelled before encountering the gas. Depending on the redshift, absorption will happen in different regions of the spectrum of the quasar's light. In consequence, the quasar light examined by observers here on Earth can be decoded to show not only the amount of hydrogen the light has encountered, but the entire history of encounters: not only the fact that some of the light has been absorbed, but where along the line of sight the absorption took place.

In this way, quasars become potent tools that allow astronomers to study intergalactic atoms residing between the quasars and Earth. The drawback is that the hyper-luminous episodes that transform a galactic nucleus into a bright quasar last only a tiny fraction of a galaxy's lifetime. In consequence, quasars are correspondingly rare on the sky, and are typically separated by hundreds of millions of light years from one another. In other words: we need to be very lucky to find a quasar in any one particular location on the sky. Quasars provide only very sparse opportunities to "X-ray" selected portions of the intergalactic medium.

A matter of different length scales

A spatial distribution can exhibit interesting structures on a range of different length scales. The filaments of the cosmic network can be hundreds of millions of light-years long or longer. But their density structure can vary on much shorter scales – for instance, each filament can have a certain density at this particular location, but a slightly different density a few thousand light-years on. If we want to test the cosmological simulations comprehensively, we will need to compare their predictions with observations on all the different length scales.

In the radial direction, comparing more and less distant regions, the technique using the cosmological redshift does not allow for the study of short length scales. The redshift of absorption lines is influenced by the motion of the gas clouds as a whole and by the motion of the atoms in the clouds (Doppler shift); on small scales, there is no clean separation between these effects and the effect of the cosmological redshift.

Thus in order to study the web's changing density on a scale of, say, ten thousand light years, we need to target areas on the sky that lie almost in the same direction, corresponding to regions of the cosmic web that are side by side, ten thousand light years apart, and compare their densities.

The problem is that each single quasar will only give us one glimpse of the cosmic web. To compare regions, we would need at least two glimpses, and in close proximity. This is where the scarcity of quasars becomes a problem.

The search for quasar pairs

A sizeable part of the work of Joseph Hennawi and his collaborators over the last few years was dedicated to solving this problem by finding ultra-rare pairs of quasars, that is, quasars that are right next to each other on the sky. Given that finding a quasar in a particular region is rare enough, the requirement of finding two quasars right next to each other makes these quasar pairs exceedingly rare. Normally one would have to observe 10,000 pairs of objects before finding a quasar pair, making the search for quasar pairs appear hopelessly inefficient.

Hennawi pioneered the application of algorithms from "machine learning", a branch of artificial intelligence, to efficiently locate quasar pairs in the massive amounts of data produced by digital imaging surveys of the night sky.

Hennawi led an independent research group at the Max Planck Institute for Astronomy (MPIA) from 2009 – 2016; during that time, he and his collaborators conducted a systematic search for quasar pairs in the data bases of large surveys, like the Sloan Digital Sky Survey, the Baryonic Oscillation Spectroscopic Survey (BOSS), and the 2dF quasar redshift survey. Owing to these efforts, several hundreds of pairs of quasars are now known. But since the spectroscopy of these surveys is not suited to mapping the spectra of very close quasar pairs, the astronomers needed to take custom spectra of the pairs they had identified.

Quasar pairs, observations, and statistics

Once a quasar pair is found, it can be used to study subtle differences in the absorption of intergalactic atoms measured along the two lines of sight. Even then, it is anything but straightforward to make deductions about the structure of the cosmic web from what is, after all, still a fairly limited sample of glimpses.

When Alberto Rorai started to work as a PhD student at the Max Planck Institute in 2011, the current project, of developing a new method to measure the small-scale structure of the cosmic web from quasar pairs, was conceived. Rorai's task was to develop the appropriate mathematical and statistical tools for the job. To this end, Rorai developed different analysis techniques that were tailored to the questions the researchers were most interested in answering. One such question is the way that gas pressure serves to disperse particularly dense regions, smoothing the structure of the cosmic web on small scales.

Rorai applied his tools to spectra of 25 quasar pairs obtained with Hennawi and other colleagues on the largest telescopes in the world, including the 10 meter Keck telescopes at the W. M. Keck Observatory on Mauna Kea, Hawaii, as well as two telescopes located in the Chilean Atacama Desert: the 8 meter Very Large Telescope (VLT) at the European Southern Observatory (ESO) and the 6.5 meter Magellan telescope at Las Campanas Observatory. Light from these quasars has taken between 10.4 and 12.3 billion years to reach us ($z = 2.0$ to 4.4). Absorption features in the light of these quasars can show us features of the cosmic web as it was between 1.4 and 3.3 billion years after the Big Bang. The quasar pairs are so close together that they allow exploring web on a scale of a few hundred thousand light-years – almost the length scale of individual large galaxies.

The aftermath of re-ionization

The astronomers compared the result of this analysis to supercomputer models that simulate the formation of cosmic structures from the Big Bang to the present. In these models, there are certain parameters that describe the temperature variations within the gas of the cosmic web. These parameters, in turn, contain information about cosmic history between about 650 million and 2.2 billion years after the Big Bang. In this time period, known as reionization, the intense radiation from the first stars, and from active nuclei from some of the first galaxies, heated up and ionized the intergalactic hydrogen and helium – an important phase transition in cosmic history.

Over the following billions of years, the gas in the cosmic web slowly cooled. But temperature variations are correlated with density fluctuations – wherever the temperature rises, the gas will expand, reducing its density. These density modifications are much more long-lived than the temperature differences, and preserve a record of the temperature structure: By measuring small-scale fluctuations using quasar pairs, it is possible to infer the temperature of gas in the cosmic web during the reionization period – the details of which, including the exact timing, are still one of the biggest open questions in the field of cosmology.

Comparison with simulations

Deriving these quantities by comparing simulations and observations takes massive computational effort. The simulations in question were run by José Oñorbe, a post-doctoral researcher at the Max Planck Institute for Astronomy. They incorporate both how dark matter particles flocked together after the Big Bang phase, forming the backbones of the cosmic web and the evolution of the hydrogen and helium gas clinging to the filamentary structure. The researchers compared 13 alternative possibilities for this evolution, with different parameters for the temperature structure and for the properties of the pressure smoothing out some of the inhomogeneities, with their observations. On a single laptop, these complex calculations would have required almost a thousand years to complete, but modern supercomputers enabled the researchers to carry them out in just a few days.

In the end, the astronomers found a set of parameters that agreed with their observations – linking quasar pair observations to the small-scale structure of the Universe around 11 billion years ago, to the thermal history after the re-ionization era. This is good news for the current models of cosmic evolution: there does exist a set of parameters for which these models can explain the quasar pair measurements. The parameter values themselves, determined by the comparison, fill in important details about the re-ionization phase. Specifically, the comparison shows significant smoothing on length scales of 200,000 to 300,000 light-years in the present Universe – which is in line with the prediction of the best current estimates for structure formation and re-ionization.

Both Hennawi and Rorai have since moved on from MPIA: Hennawi to the University of California, Santa Barbara, in 2015, where he took up a professorship; Rorai moved on to a postdoc position at the University of Cambridge in 2014.

Alberto Rorai (also University of Cambridge),
Joseph F. Hennawi
(also University of California at Santa Barbara [UCSB]),
Jose Oñorbe, Girish Kulkarni
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Martin White
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and Khee-Gan Lee (LBL)

A. Rorai et al. 2017: "Measurement of the Small-Scale Structure of the Intergalactic Medium Using Close Quasar Pairs" in Science, Vol. 356 , pp. 418-422. DOI: 10.1126/science.aaf9346

II.5 Highlight

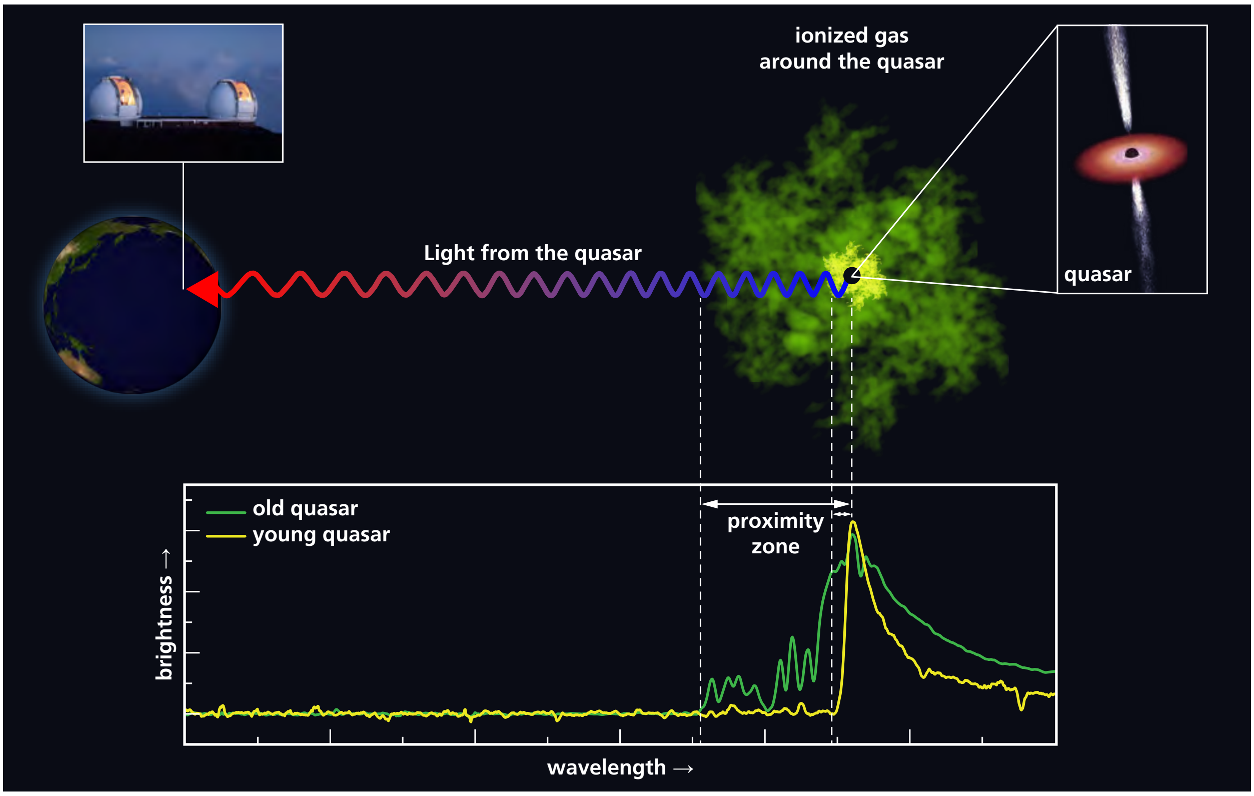
Discovery in the early universe poses black hole growth puzzle

Quasars are luminous objects with supermassive black holes at their centers, visible over vast cosmic distances. Infalling matter increases the black hole mass and is also responsible for a quasar's brightness. Using the W.M. Keck observatory in Hawaii, astronomers led by Christina Eilers have discovered extremely young quasars with a puzzling property: these quasars have the mass of about a billion suns, yet have been collecting matter for less than 100,000 years. Conventional wisdom says quasars of that mass should have needed to pull in matter a thousand times longer than that – a cosmic conundrum.

Fig. II.5.1: Basic set-up of the quasar observations: Light from a quasar *(right)* is absorbed by gas. Absorption is much less in the quasar's proximity zone, which is shown in green for an older quasar, in yellow for a younger quasar. The extent of the proximity zone can be read off the spectrum *(bottom)*. The quasar itself is a central black hole, surrounded by a disk of swirling matter, and possibly sending out particles in two tightly focussed jets *(inset, top right)*.

Within the heart of every massive galaxy lurks a supermassive black hole. How these black holes formed, and how they have grown to be as massive as millions or even billions of suns, is an open question. At least some phases of vigorous growth are highly visible to astronomical observers: Whenever there are substantial amounts of gas swirling into the black hole, matter in the direct vicinity of the black hole emits copious amounts of light. The black hole has intermittently turned into a quasar, one of the most luminous objects in the Universe.

Researchers from the Max Planck Institute for Astronomy (MPIA) have discovered three quasars that challenge conventional wisdom on black hole growth. These quasars are extremely massive, but should not have had sufficient time to collect all that mass. The discovery, which is based on observations at the W.M. Keck observatory in Hawaii, glimpses into ancient cosmic history: Because of their extreme brightness, quasars can be observed out to large distances. The astronomers observed quasars whose light took nearly 13 billion years to reach Earth. In consequence, the observations



Credit: A.-C. Eilers / MPIA graphics department

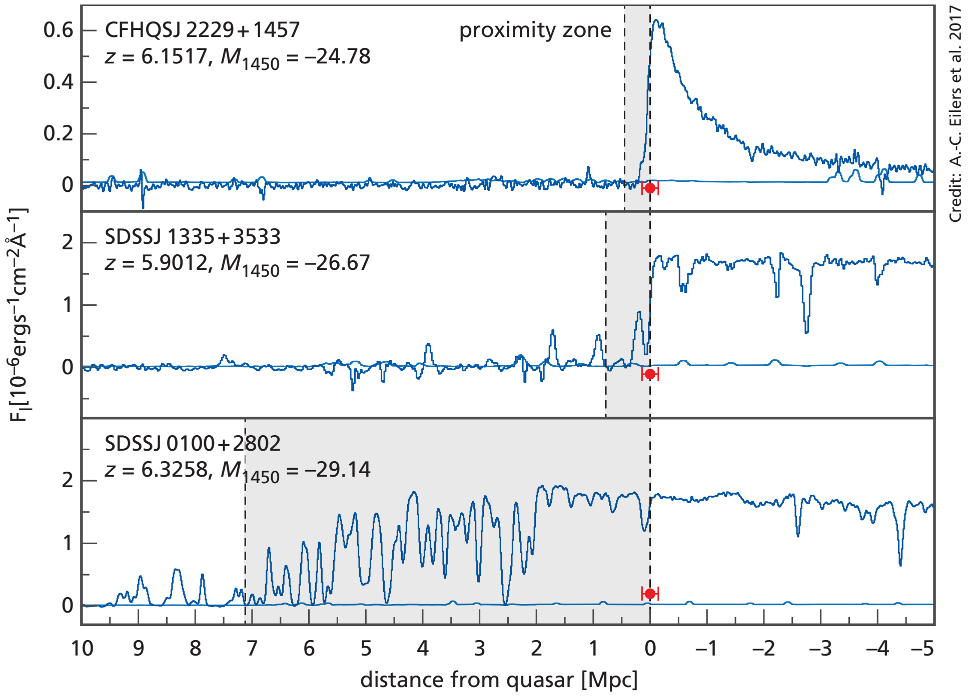


Fig. II.5.2: Three quasar spectra from three different epochs in cosmic time, showing proximity zones of different sizes.

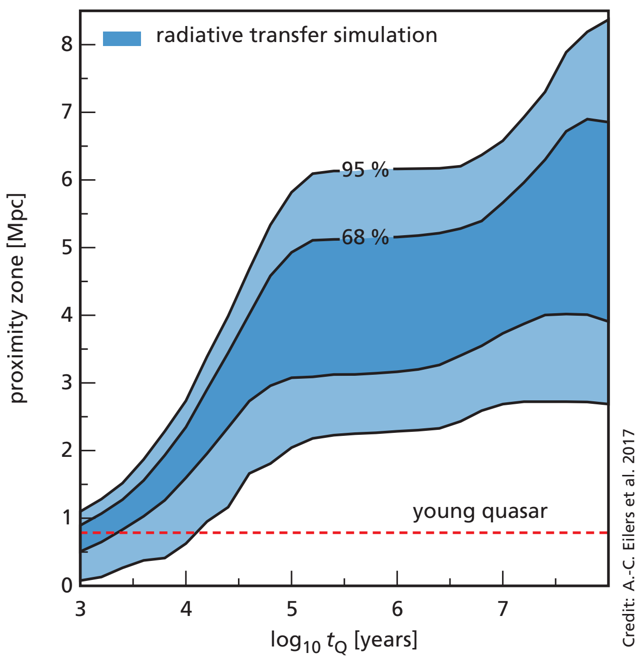
show these quasars not as they are today, but as they were almost 13 billion years ago, less than a billion years after the Big Bang.

The quasars in question have about a billion times the mass of the Sun. All current theories of black hole growth postulate that, in order to grow that massive, the black holes would have needed to collect infalling matter, and shine brightly as quasars, for at least a hundred million years. But these three quasars proved to be have been active for a much shorter time, less than 100,000 years. "This is a surprising result," explains Christina Eilers, a doctoral student at MPIA and lead author of the present study. "We don't understand how these young quasars could have grown the supermassive black holes that power them in such a short time."

To determine how long these quasars had been active, the astronomers examined how the quasars had influenced their environment – in particular, they examined heated, mostly transparent "proximity zones" around each quasar. "By simulating how the light from quasars ionizes and heats gas around them, we can predict how large the proximity zone of each quasar should be," explains Frederick Davies, a postdoctoral researcher at MPIA who is an expert in the interaction between quasar light and intergalactic gas. Once the quasar has been "switched on" by infalling matter, these proximity zones grow very quickly. "Within a lifetime of 100,000 years, quasars should already have large proximity zones."

Surprisingly, three of the quasars had very small proximity zones – indicating that the active quasar phase cannot have set in more than 100,000 years earlier. "No current theoretical models can explain the existence of these objects," says Professor Joseph Hennawi, who leads the research group at MPIA that made the discovery. "The discovery of these young objects challenges the

Fig. II.5.3: Evolution of proximity zone size over time: results from radiative-transfer simulations.



existing theories of black hole formation and will require new models to better understand how black holes and galaxies formed."

The astronomers have already planned their next steps. "We would like to find more of these young quasars," says Christina Eilers, "While finding these three unusual quasars might have been a fluke, finding additional examples would imply that a significant fraction of the known quasar population is much younger than expected." The scientists have already applied for telescope time to observe several additional candidates. The results, they hope, will constrain new theoretical models about the formation of the first supermassive black holes in the universe – and, by implication, help astronomers understand the history of the giant supermassive black holes at the center of present-day galaxies like our own Milky Way.

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A.-C. Eilers et al. 2017: "Implications of $z \sim 6$ Quasar Proximity Zones for the Epoch of Reionization and Quasar Lifetimes" in The Astrophysical Journal, Vol. 840, article id. L24. DOI: 10.3847/1538-4357/aa6c60

II.6 Highlight

First radio detection of lonely planet disk shows similarities between stars and planet-like objects

First radio observations of the lonely, planet-like object OTS44 reveal a dusty protoplanetary disk that is very similar to disks around young stars. This is unexpected, given that models of star and planet formation predict that formation from a collapsing cloud, forming a central object with surrounding disk, should not be possible for such low-mass objects. Apparently, stars and planet-like objects are more similar than previously thought.

A new study of the lonely, planet-like object OTS44 has provided evidence that this object has formed in a similar way as ordinary stars and brown dwarfs – a surprising result that challenges current models of star and planet formation. The study by a group of astronomers, led by Amelia Bayo of the Universidad de Valparaíso and involving several astronomers from the Max Planck Institute for Astronomy, used the ALMA observatory in Chile to detect dust from the disk surrounding OTS44.

From collapsing clouds to stars

Stars are formed when part of a giant cloud of gas collapses under its own gravity. But not every such collapse results in a star. The key criterion is one of mass: If the resulting object has sufficient mass, its gravity is strong enough to compress the central regions to such high densities, and heat them to such high temperatures, that nuclear fusion sets in, turning hydrogen nuclei (protons) into helium. The result is, by definition, a star: an object bound by its own gravity, with nuclear fusion in its core region, shining brightly as the energy liberated during the fusion processes is transported outwards.

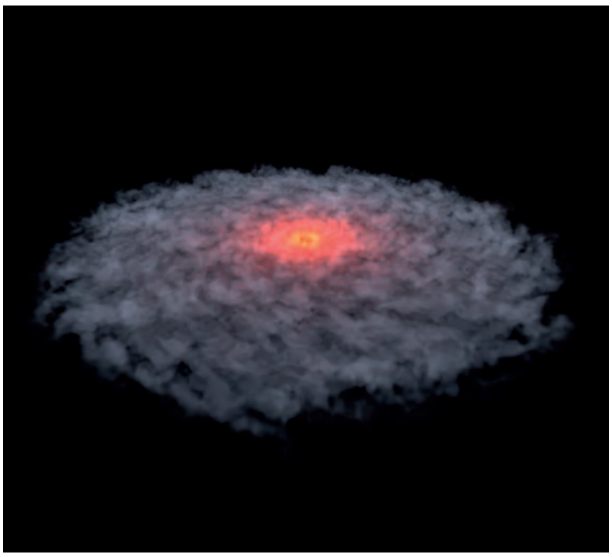
Initially, the newly born star is surrounded by the remnants of the collapsed cloud. But in the natural course of collapsing, both the star and the cloud have begun to rotate at an appreciable rate. The rotation serves to flatten the material surrounding the young star, forming what is known as a protoplanetary disk of gas and dust. True to its name, this is where planets begin to form: The dust clumps to larger and larger grains and pebbles, increasing in size until, finally, the resulting objects are large enough to join together under the influence of its own gravity, forming solid planets thousands or even tens of thousands kilometers in diameter like our Earth, or collecting appreciable amounts of the surrounding gas to form gas giants, like Jupiter in our solar system.

If the object resulting from the collapse of the initial cloud has between 0.072 and 0.012 times the mass of the Sun – which corresponds to between 75 and 13 times the mass of Jupiter – what emerges is called a brown dwarf: a failed star, with some intermittent fusion reactions of deuterium (heavy hydrogen, consisting of one proton and one neutron) in the core regions, but no sustained, long-lasting phase of hydrogen fusion.

The strange case of OTS44

Can collapse produce even lighter objects, with similar masses as that of planets? A thorough analysis of the object OTS44, published in 2013 by a group of astronomers led by Viki Joergens from the Max Planck Institute for Astronomy (MPIA), presented strong evidence that this is indeed the case. OTS44 is a mere two million years old – in terms of stellar or planetary time-scales a newborn baby. The object has an estimated 12 Jupiter masses and is floating through space without a close companion. It is part of the Chamaeleon star forming region in the Southern constellation Chamaeleon, a little over 500 light-years from Earth, where numerous new stars are in the process of being born from collapsing clouds of gas and dust.

Fig. II.6.1: Artist's impression of the gas and dust disk around the planet-like object OTS44. First radio observations indicate that OTS44 has formed in the same way as a young star.



Credit: J. Olofsson (U. Valparaiso & MPIA)

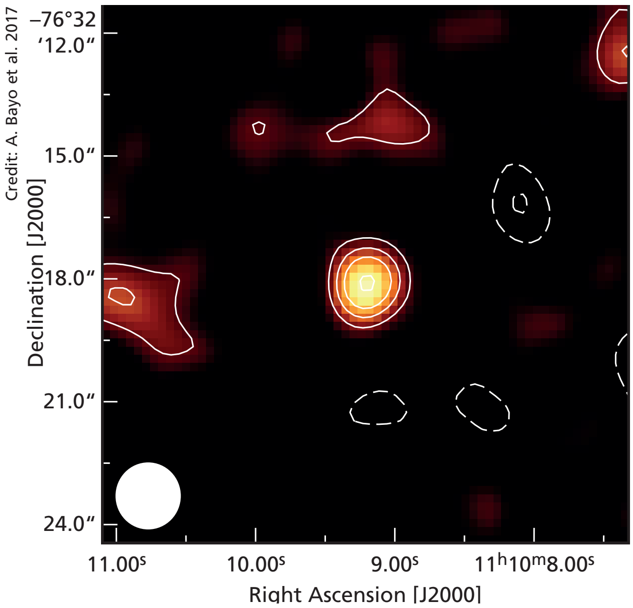


Fig. II.6.2: ALMA millimetre wave (Band 6) image of OTS44. The beam size (as a measure of resolution), 1.6 times 1.6 seconds of arc, is shown in white in the lower left corner. Dashed white line contours indicate areas of varying intensity.

Just like a young star, OTS44 is surrounded by a disk of gas and dust, one of only four known low-mass objects (with about a dozen Jupiter masses or less) known to harbour a disk. Most conspicuously, OTS44 is still in the process of growing – that is, drawing material from the disk onto itself at a substantial rate. The disk itself is quite substantial; both this disk and the infalling material (accretion) are telltale signs of the standard mode of star formation – an indication that there is no fundamental difference between the formation of low-mass objects such as OTS44 and the formation of ordinary stars. OTS44 probably has the lowest mass of all objects where both a disk and infalling material have been detected.

Brown dwarf vs. planet-like object

We have so far avoided calling OTS44 either a brown dwarf or something else. In fact, nomenclature varies: Some astronomers call every object that has formed by direct collapse and is not a star a brown dwarf; by this criterion, only objects that form in disks around a central object can be planets. There is an alternative definition that hinges on the fact that an object like OTS44 does not have sufficient mass for a significant episode of deuterium fusion, and does not qualify as a brown dwarf on that account. We will compromise by referring to OTS44 as a planet-like object.

While the case of OTS44 shows that even planet-like objects can form by collapse, the details are anything but clear. For the formation of comparatively low-mass objects, be they very light stars, or brown dwarfs, or lonely planets, there are two main possibilities – but both are problematic in the case of OTS44. The first possibility is a direct collapse by a small isolated cloud. But going by our current knowledge, such a direct collapse should not be able to form such a planetary-mass object without an intermediate stage.

Much more likely is the alternative, namely that OTS44 could have formed as part of a larger collapsing cloud, when the collapsing regions fragmented, producing several objects, including OTS44, instead of a single larger body. But this does not mesh well with the observations. Currently, OTS44 is not part of any multiple system. And even if we assume it was somehow ejected from such a system, OTS44 is still very young, and could not have moved far from its natal environment – and that system would not have had time to dissolve completely into separate stars and/or brown dwarfs. But there is only one single object within 10,000 astronomical units (10,000 times the average Sun-Earth-distance) of OTS44, where the siblings of OTS44 could reasonably be expected, and there are no signs that this object was part of a collapsing, fragmenting cloud.

Tracking dust with ALMA

Clearly, there is more to be learned. That is what motivated a group of researchers led by Amelia Bayo to find out more about OTS44. The group includes a number of researchers from the Max Planck Institute for Astronomy (MPIA), as well as several former MPIA astronomers. Amelia Bayo was herself a postdoctoral researcher at MPIA before moving on to the Universidad de Valparaíso, Chile and in science, the international stations of an astronomer's career often result in collaboration networks – in this case, a strategic collaboration between astronomers at the Universidad de Valparaíso and the MPIA's Planet and Star Formation Department led by Thomas Henning. The two institutions have an additional link: the Universidad de Valparaíso hosts an astronomical Max Planck Tandem Group, which commenced work in early 2017. With such tandem groups, the Max Planck Society fosters international cooperation with specific excellent research institutions.

In this particular case, the group gathered by Bayo for observing OTS44 included several members with the necessary skills and experience to make full use of the ALMA observatory: a constellation of 50 radio antennae for detecting millimeter and submillimeter radiation, operated by an international consortium and located in the Atacama desert in Chile.

The astronomers applied for ALMA time to observe the disk of OTS44 at millimeter wavelengths. Such wavelengths are particularly suited to detect dust grains, which are present in protoplanetary disks (and account for one percent or more of the disk mass; these mass estimates are a subject of ongoing research). At least in the disks around more massive objects, these dust grains are the seeds of planet formation.

Dust mass and a surprisingly universal relation

For millimeter waves, the disk is optically thin, in other words: observations show the millimeter radiation from all the dust in the disk. (In an optically thick disk, we would only see radiation from the surface layers; the lower layers would be obscured by the upper layers.) This allowed the astronomers to estimate the total amount of dust in the disk – although the result still depends on the disk temperature. Temperature estimates for such disks, given the measured overall luminosity, give values between 5.5 Kelvin and 20 Kelvin for the OTS44 disk. This leads to estimates for the dust mass between 0.07 times the mass of the Earth (for the highest temperature estimate) and 0.64 Earth masses (for the lowest temperature).

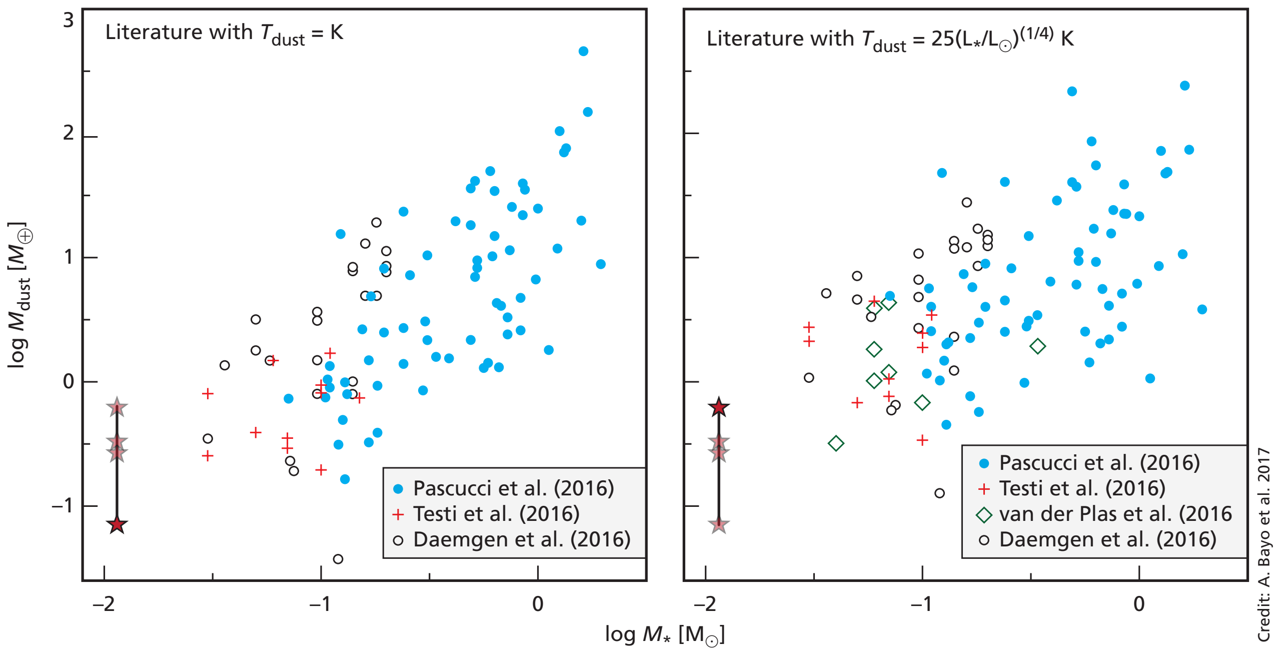
These mass estimates confirm the similarity between stars and lower-mass objects: Systematic studies had shown earlier that for young stars and brown dwarfs, there is an approximate relationship between the mass of the central object and the mass of the dust in the surrounding disk. Inserting the data points for OTS44, the lonely planet-like object fits very well into the overall picture – indicating that the same overall mechanism is involved in all these cases, putting all central objects from about a hundredth to a few solar masses onto the same footing.

Dust grains of unusual size

Another interesting consequence stems from the fact that the disk is emitting significant amounts of millimeter radiation in the first place. This indicates the presence of certain amounts of grains of dust that are about a millimeter in size. Going by the current theories of planet formation, this is surprising: such larger dust grains should not have been able to form in a disk around such a low-mass object. In such a disk, the dust grains orbit the central mass like so many microscopic planets, following the laws first found by Johannes Kepler in the early 17th century. The gas of the disk, on the other hand, has internal pressure, which makes its rotation somewhat slower. The "head wind" felt by dust grains as they move through the slower gas should slow down the smaller grains, making them drift inwards before they finally fall onto the central object. There are arguments that these detrimental effects are particularly strong in lower-mass objects. From these calculations, it follows that the dust grains in the disk should have vanished when they were somewhat smaller – and should not have had the time to clump to form the observed millimetre-size grains.

Once the millimeter-size grains are there, the situation becomes less problematic – with their larger size, these grains do not feel the head wind as acutely as their smaller kin. But the presence of these larger grains poses a puzzle – and hints at the intriguing possibility

Fig. II.6.3: Four possible determinations of the dust mass of OTS44 (red five-pointed stars) in a diagram plotting stellar mass against disk dust mass for substellar objects found in the literature. The OTS44 mass estimates differ by the values they assume for the dust temperature; each red star is labelled with value of the corresponding dust temperature. The literature values used for comparison differ according to assumptions about the dust temperature, as well. The left-hand diagram assumes a constant dust temperature of 20 Kelvin, while the right-hand diagram postulates a specific dependence of the dust temperature on the central star's luminosity.



that lonely planets might even be able to grow even larger dust grains, and may be even go as far as forming downright miniature moons, in their surrounding disks.

Similarities with young stars

All, in all, the new results make OTS44 look more and more similar to a young star, surrounded as it is by a disk, given the earlier evidence that it is still growing by incorporating material from that disk, and now with the new evidence that the ratio of the dust mass to the mass of the central object follows the same relation as for brown dwarfs and stars.

Evidently, the current models that preclude low-mass objects from forming in this particular way, via the collapse of a cloud of gas, are missing something. Observations like these new ones for OTS44 can be hoped to point us in the right direction for what that missing something might be, and thus towards a better understanding of the formation of low-mass objects in the Universe.

Viki Joergens, Yao Liu (also Purple Mountain Observatory, Nanjing, China), Johan Oloffson (also Universidad de Valparaíso), Thomas Henning, and Henrik Beuther

in collaboration with

Amelia Bayo (first author; Universidad de Valparaíso [UV]), Robert Brauer (University of Kiel), Javier Arancibia (UV), Paola Pinilla (University of Arizona), Sebastian Wolf, Jan Philipp Ruge (both University of Kiel), Antonella Natta (Dublin Institute for Advanced Studies and INAF-Osservatorio Astrofisico di Arcetri), Katharine G. Johnson (University of Leeds), Mickael Bonnefoy (IPAG Grenoble), and Gael Chauvin (IPAG Grenoble and Unidad Mixta Internacional Franco-Chilena de Astronomía, Santiago)

A. Bayo et al. 2017: "First Millimeter Detection of the Disk around a Young, Isolated, Planetary-mass Object" in Astrophysical Journal Letters, Vol. 841, article id. L11. DOI: 10.3847/2041-8213/aa7046

II.7 Highlight

Newly discovered fast-growing galaxies could solve cosmic riddle – and show ancient cosmic merger

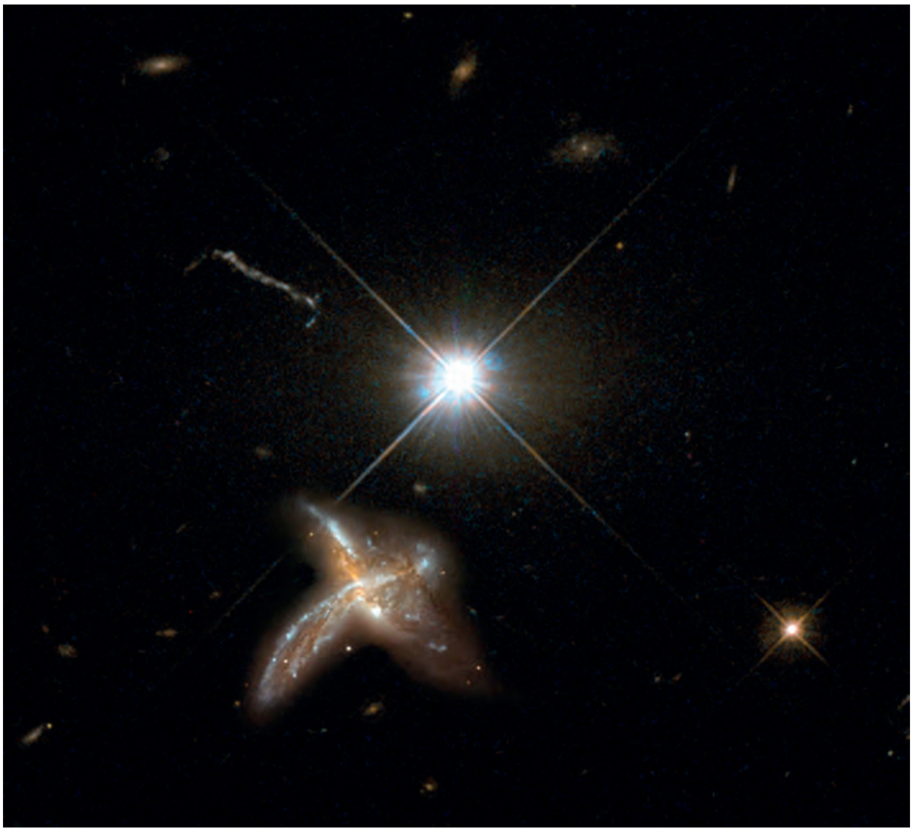
Astronomers have discovered a new kind of galaxy in the early Universe, less than a billion years after the Big Bang. These galaxies are forming stars more than a hundred times faster than our own Milky Way. The discovery could explain an earlier finding: a population of suprisingly massive galaxies at a time 1.5 billion years after the Big Bang, which would require such hyper-productive precursors to grow their hundreds of billions of stars. The observations also show what appears to be the earliest image of galaxies merging.

A group of astronomers led by Roberto Decarli at the Max Planck Institute has discovered surprisingly productive galaxies in the very early Universe. These galaxies, which we see as they were less than a billion years after the Big Bang, produce more than hundred solar masses worth of stars every year – and could be the key to explaining a population of somewhat later unusually massive galaxies that other astronomers had discovered in the early Universe, about 1.5 billion years after the Big Bang. Those later massive galaxies posed a particular kind of puzzle: While less than a billion years old themselves, they contain numerous reddish stars almost as old as these galaxies themselves, indicating that they must have been forming stars at a high rate for almost all of their existence.

Understanding cosmic history

On the one hand, the history of the Universe as a whole is simpler than the history of Earth's human inhabitants. Cosmological history directly follows simple fundamen-

Fig. II.7.1: Artist's impression of a quasar and neighboring merging galaxy. The galaxies observed by Decarli and collaborators are so distant that no detailed images are possible at present. This combination of images of nearby counterparts gives an impression of how they might look in more detail.



Credit: NASA/ESA Hubble Space Telescope / MPIA graphics department tal laws, namely the laws of physics. On the other hand, this ups the ante for cosmologists: They should be able to explain in terms of physical processes how the universe has reached its present state from a fairly boring, almost homogeneous beginning directly after the Big Bang, 13.8 billion years ago.

There are several key classes of objects whose properties and evolution need explaining. First of all, there is dark matter, which does not interact with light and other forms of electromagnetic radiation at all. Over the past 13.8 billion years, dark matter has clumped together under its own gravity, forming the gigantic filaments of the cosmic web, the backdrop or framework of cosmic history. On smaller scales, dark matter has formed loose, almost spherical associations known as halos. Gas collecting in those halos has formed galaxies: collections of between hundreds of thousands and hundreds of billions of stars, suffused with (mostly hydrogen) gas.

To the best of current astronomical knowledge, every massive galaxy contains a supermassive black hole in its central regions, with masses between a few hundred thousand and a few billion times the mass of the Sun. (The central black hole of our own galaxy has a mass of 4 million solar masses.) When sufficient amounts of matter fall into such a supermassive black hole, it turns into a quasar: directly before falling into the black hole, matter collects in a swirling disk; this "accretion disk" is heated up as more and more infalling matter deposits its energy; the extreme temperature of the disk (think "incandescent light bulb") and additional effects make the quasar into one of the brightest objects in the universe, as bright as all the stars of a large galaxy combined.

In addition to stars, and rare and transient phenomena like quasars, there is intergalactic gas – again, mostly hydrogen, both in the galaxies themselves and filling the void between galaxies, and between the filaments of the cosmic web.

Cosmic history on display

Cosmic history describes the formation and the evolution of these objects, including their interactions. How and when did galaxies form their stars? Is intergalactic gas funneled into galaxies, providing new raw material for star formation? Does quasar activity hinder or encourage star formation? Is star formation the same throughout history, or did galaxies become less productive, or more productive, over time? By now, the field of cosmic historiography can provide at least some answers. Open questions are pursued using modeling, simulations, and observations – including recent massive surveys that enable statistics with samples of hundreds of thousands of objects.

Astronomical distances are so large that it takes the light of distant objects an impressive time to reach us here on Earth. That provides astronomers with a cross section of cosmic history. For instance, we see the Andromeda galaxy as it was 2.5 million years ago, since Andromeda's light has taken 2.5 million years to reach us. Other galaxies, we see as they were billions of years ago.

Thus, while we cannot follow the entire history of any single object, astronomical observations do show us the different stages of cosmic history. Assuming that at least on average, no location within the universe is markedly different from any other – for instance, that we will find the same numbers of galaxies, or quasars, with the same average properties –, we can observe distant objects as they once were, and draw conclusions about our own past.

An unusual population of massive galaxies

Cosmology must take the many observations that represent different epochs of cosmic history and weave them into a consistent physical narrative: Objects that have been found in one particular epoch must have formed in some earlier epoch. One example is the discovery of a substantial population of very massive galaxies, each with hundreds of billions of stars and a total mass of hundreds of billions of solar masses, in an epoch around 1.5 billion years after the Big Bang ($z \sim 4$) by Caroline Straatman (then Leiden University, now at MPIA) and collaborators in 2014.

Once this observation has been made, it needs to be explained. For there to be galaxies that rich in stars at a time of 1.5 billion years after the Big Bang, when the Universe was a bit more than 10% its present age, the precursors of these galaxies must have formed stars at an enormous rate at earlier epochs.

But do we see evidence for such actively star-forming galaxies in the very early Universe?

A serendipitous discovery

The new results by Roberto Decarli and collaborators described here have shed new light on this question – albeit serendipitously, as the astronomers' initial aim had been somewhat different. Using the ALMA observatory, they were looking for very distant star-forming host galaxies of quasars. Since quasars are galactic nuclei, each is embedded in what is known as its host galaxy. There have long been questions about the interaction of quasars with their host galaxies – do they, for instance, inhibit star formation in the galaxy surrounding them?

More generally, what are the properties of these host galaxies – and are they related to the fact that the galaxy is hosting a quasar? To address such questions, Decarli and his colleagues studied known quasars so distant they represent the first billion years of cosmic history – and in targeting these quasars, they looked specifically for emission associated with star-forming activity.

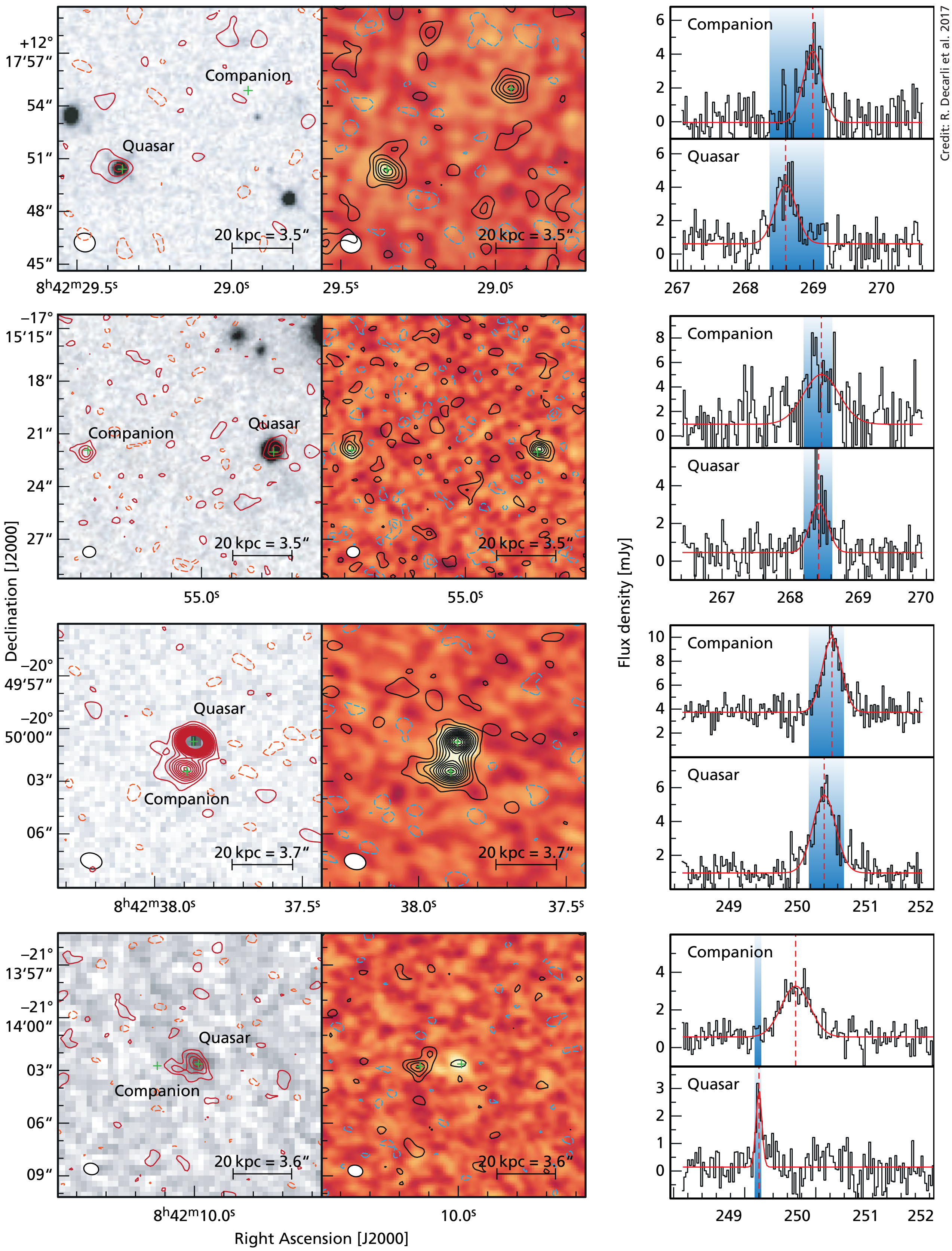


Fig. II.7.2: *Left column:* grayscale near-infrared images overlaid with red countours for the 1.2 mm radiation from the dust continuum, observed with ALMA. The infrared images were obtained (*top to bottom*) with the Hubble Space Telescope, the LBT, the NTT and the MPG/ESO 2.2 meter telescope. *Central column:* Continuum-subtracted ALMA [C II] line maps shown as contours. The background is the 1.2 mm continuum flux density. *Right column:* Spectra of the [C II] emission and underlying continuum emission of the quasars and their companions.

Signs of star formation activity

Star formation involves gas clouds collapsing under their own gravity. If gravity is strong enough to compress the central regions to such high densities, and heat them to such high temperatures, that nuclear fusion sets in, turning hydrogen nuclei (protons) into helium. The result is, by definition, a star: an object bound by its own gravity, with nuclear fusion in its core region, shining brightly as the energy liberated during the fusion processes is transported outwards. But in order to reach these high densities, and such an advanced state of collapse, the cloud needs to cool down during the collapse.

That is surprisingly difficult: Hydrogen molecules, it turns out, are not very efficient in radiating away heat in the form of light. Most of the cooling-down is mediated by a kind of atom that occurs only very rarely in such collapsing clouds, but is able to radiate energy very efficiently: carbon. There are typically only three carbon atoms for each 100,000 hydrogen atoms in a modern-day star-forming environment, but in particular in its singly ionized form, with one electron having broken free from the atom, carbon is a highly efficient radiator, shining brightly in a very narrow frequency range known among astronomers as the [C II] line.

(The square brackets indicate that this is a line that is only visible under the rarified conditions of outer space – in laboratory experiments at higher gas density, the atoms in question are more likely to lose their energy by colliding with other atoms, before they can radiate [C II] light.)

Starforming regions are the main source of [C II] light in galaxies. Conversely, by measuring the amount of [C II] light emitted by a galaxy, one can estimate the rate at which that galaxy is forming new stars.

Distant star formation with ALMA

For close-up objects, the [C II] line has a wavelength of 158 μm, in the far infrared range of the spectrum. Unfortunately, the Earth's atmosphere is virtually opaque for light at that wavelength, and observations of this kind can only be made by airborne or space observatory, most recently SOFIA and Herschel.

For very distant objects, though, there is an additional effect that makes ground-based observations possible. For an observer on Earth, the light of very distant objects is stretched by the so-called cosmological redshift, an effect of the expansion of the Universe. For the galaxies and quasars that Decarli and his colleagues were aiming at, light is stretched by a factor of about seven (corresponding to a z value $z \sim 6$), bringing the line into the millimeter wave regime, which is observable using ground-based telescopes like ALMA. That allows for high-resolution, sensitive observations.

ALMA is a telescope array composed of about 50 high-precision antennas, operated by an international consortium in the Atacama desert in Chile, and represents a significant increase in sensitivity over previous such observatories. Before the present study, [C II] investigations on high redshift ('high-z') quasar host galaxies had only been done in small samples (with up to four quasars per study). With ALMA, bigger samples became feasible: Decarli and his colleagues obtained sensitive [C II] data for 25 galaxies.

Not the galaxies they were looking for

And for four of these targets, the astronomers were in for a surprise. Yes, there were quasars in those images, but there were galaxies as well. Not the quasars' host galaxies, but companion galaxies, each a little offset from the quasar target. And these were galaxies that were shining brightly in [C II], evidently forming more than a hundred solar masses' worth of stars per year. In galactic terms, that is quite a lot. Our home galaxy, for instance, forms no more than one solar mass per year. The other galaxies astronomers had previously found in this period of the early universe had star formation rates between one and ten solar masses per year.

The objects observed by Decarli and colleagues are so distant that we see them as they were a bit more than 900 million years after the Big Bang ($z \sim 6$). But at that rate of forming new stars, these galaxies could indeed be the precursors of the star-rich galaxies found by Straatman and her colleagues at 1.5 billion years after the Big Bang ($z \sim 4$).

The group around Decarli found a possible missing piece of the puzzle of cosmic history: a population of young, vigorously star-forming galaxies at a time 900 million years after the Big Bang. If this type of galaxy is sufficiently common, it could explain the unexpectedly star-rich galaxies about 600 million years later.

Quasars, overdensities and star formation

In all probability, finding these galaxies so close to quasars is no coincidence. The details will need to be examined much more thoroughly, including additional observations, but one general correlation suggests itself: In order to explain how the black holes driving quasars were able to amass a billion solar masses that early in the history of the Universe, these quasars should be located in the highest-density regions of the Universe at that time. It is plausible that the same overdense environment was conducive to the formation of the newly found, quickly star-forming galaxies as well. Thus, one would be more likely to find these galaxies in the neighbourhood of quasars.

Either alternatively or in addition, it is possible that the quasar's activity encouraged the nearby galaxy to form more stars, for instance by pushing on that galaxy's gas

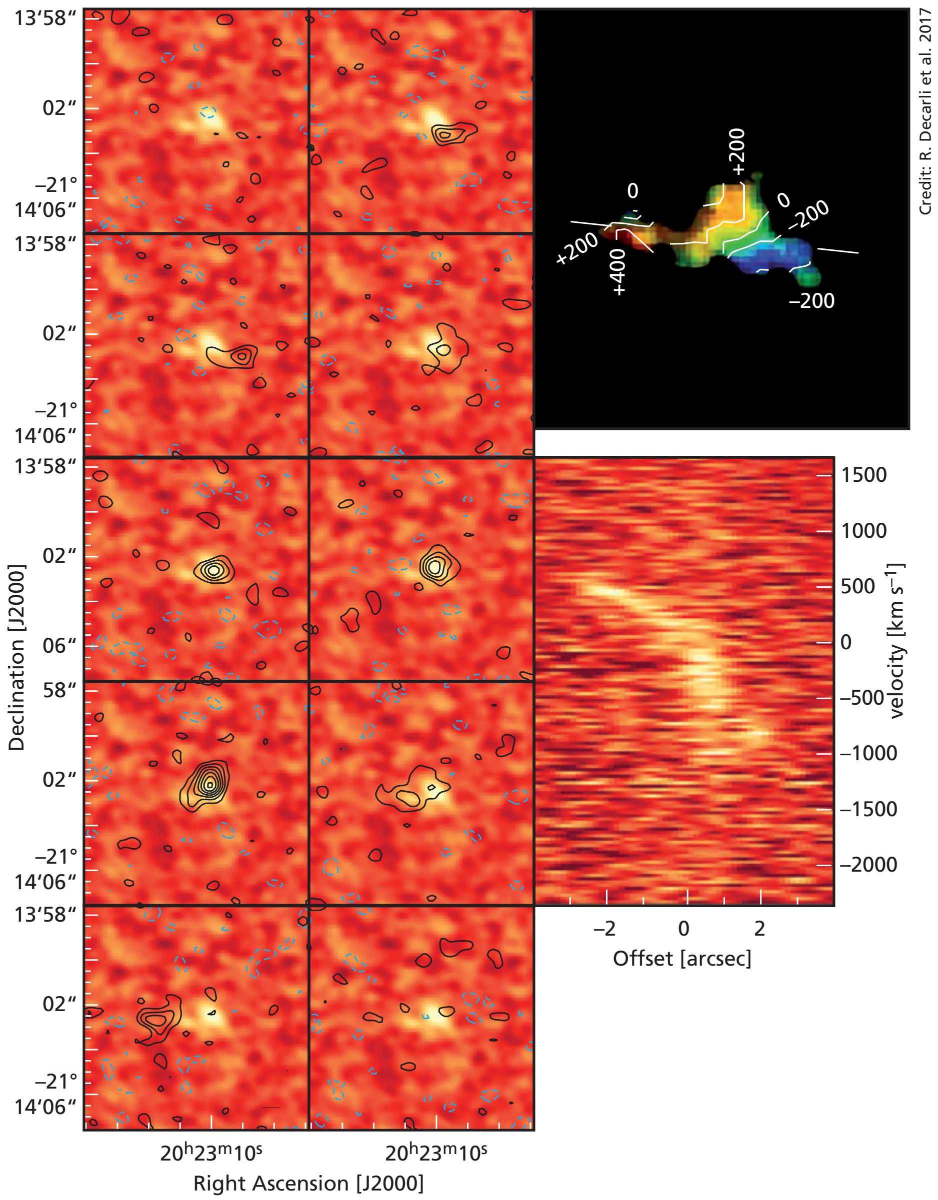


Fig. II.7.3: *Two columns on the left*: Continuum-subtracted [C II] channel maps of PJ 308-21 and its companion shown as contours. Background colour image: underlying continuum. *Top right:* velocity field (*colour scale*) of PJ 308-21, with iso-velocity lines marked in white. *Bottom right:* position-velocity diagram along the white straight line in the velocity field image.

from the outside, setting off more local cloud collapses than would otherwise have happened.

If these newly discovered active galaxies are representative of a more widespread population of vigorously star-forming galaxies in the very early Universe, occurring even in the many regions where there are no quasars (albeit more rarely), they would be sufficient to account for the massive, evolved galaxies discovered by Straatman and collaborators.

The first known merger?

One of the four objects, the quasar with the catalogue number PJ 308-21, is particularly interesting. Its star-forming companion galaxy is comparatively close to the quasar, and appears to be stretched out into a long shape towards the quasar. This kind of deformation is to be expected, if the companion galaxy is interacting with the quasar host galaxy.

This kind of interaction, each galaxy distorted with tidal forces of the other galaxy's gravity, commonly is the prelude to the merger of these galaxies, resulting in the formation of a larger single galaxy. In the current models of galaxy evolution, this is a key mechanism for how galaxies have grown in the course of cosmic history. If the new observation indeed shows a galaxy merger, it would be the earliest known such merger.

All in all, the newly discovered population has shown us one piece of the cosmic narrative, namely how the somewhat later, star-rich galaxies formed. It is also pointing astronomers in a specific direction to find out more about the history of the early Universe, namely towards an investigation of the role of overdensities, and of possible interactions, in the formation of the quasars and their companions.

Further steps

Next, Decarli and his colleagues will need to fully characterize their newly discovered sources: Since these galaxies do not show obvious signs of accreting central black holes, which would outshine the faint stellar emission of the host galaxy, and which might influence star-formation in the galaxy, these newly discovered galaxies are an ideal laboratory to study the first stages of the formation of massive galaxies. What kinds of stars do they contain, and in what proportion? What is their total mass, and how many stars have already been formed in these galaxies? What are the properties of the gas between the stars in these galaxies, the interstellar medium – how dense is it, what is its temperature, what fraction of it is ionized? And are these galaxies indeed only found very close to quasars, or do they exist in other environments, as well?

Answering these questions will require a whole battery of telescopes: from ALMA via the Hubble Space Telescope and the Spitzer Space Telescope to various ground-based telescopes and, in the immediate future, the James Webb Space Telescope. But by analyzing the data from these telescopes, with their different specializations and strengths, astronomers should be able to write a detailed version of this particular chapter of cosmic history: how the earliest massive galaxies came into being.

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R. Decarli et al. 2017: "Rapidly star-forming galaxies adjacent to quasars at $z > 6$" in Nature, Vol. 545, pp. 457-461.
DOI: 10.1038/nature22358

II.8 Highlight

Heavy stellar traffic, deflected comets, and a closer look at the triggers of cosmic disaster

As stars pass close by our Solar System, they can nudge comets from the distant Oort cloud into the inner regions around the Sun. Thus, stellar encounters are an important factor in determining the risk of large cosmic impacts on Earth. Coryn Bailer-Jones from the Max Planck Institute for Astronomy has used data from the ESA satellite Gaia to give the first systematic estimate of the rate of such close stellar encounters. Every million years, up to two dozen stars pass within a few light-years of the Sun, making for a near-constant state of perturbation.

Strikes by large asteroids or comets are a global danger to be taken seriously – they have occurred in Earth's past, and they will occur again. The first piece of good news is that impacts with regional or even global consequences are exceedingly rare, and occur at a rate of no more than one per million years. A random person's risk of dying in a plane crash is an estimated 25 times larger than the risk of perishing due to a cosmic impact event. The second piece of good news is that current asteroid monitoring systems yield a fairly complete picture of the larger asteroids and comets – those more than a few hundred meters in diameter – that can be found in our Solar System neighborhood, and indicate reliably that none of these currently known "Near-Earth Objects" pose a concrete threat to the Earth.

Fig. II.8.1: Image of the Comet C/2012 S1 (ISON), taken with the TRAPPIST–South national telescope at ESO's La Silla Observatory on the morning of Friday, 15 November 2013, whose likely origin is the Oort cloud. This comet is definitely not colliding with Earth, but it shows the typical appearance of comets entering the inner solar system, including the typical tail and coma made of gas and dust.

Credit: TRAPPIST/E. Jehin/ESO

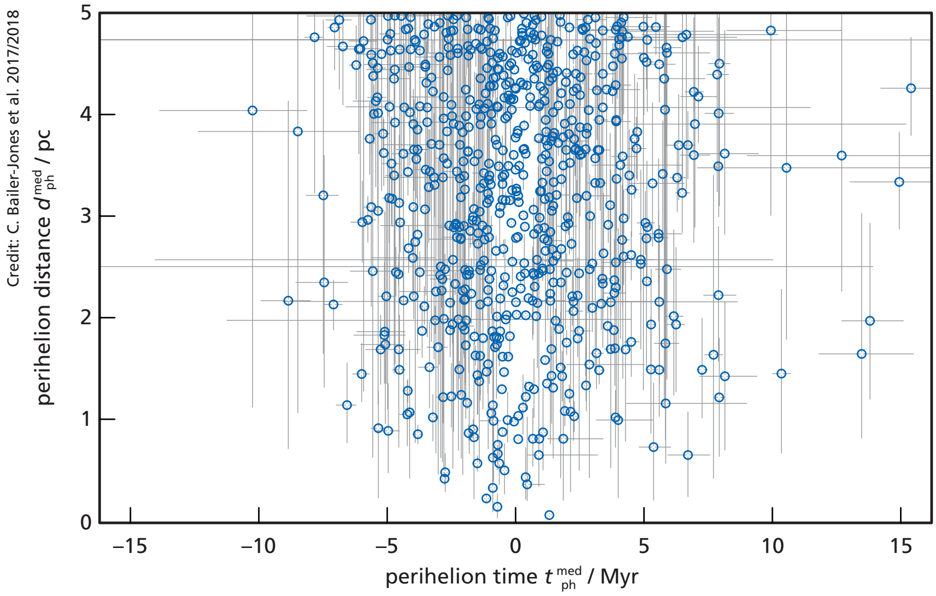


Fig. II.8.2: Distances of past and future close encounters plotted against time. Encounter time is given as the date of the object's closest approach to the Sun (perihelion), distances as the object's distance from the Sun at perihelion (in parsec = pc, 1 pc amounts to 3.2 light-years). In each case, the median values are given, as well as an error bar. The diagram is based on a modified version of the calculations described here, based on the second Gaia data release, Gaia DR2.

Understanding cosmic collisions

Still, the threat is so fundamental that scientists are eager to understand the underlying mechanisms. When it comes to impacts by comets, the chain of events leads even further into the depths of space, far beyond our Solar System. Our Sun is only one of an estimated 200 to 300 billion stars in our home galaxy, the Milky Way. Viewed from afar, you would see the Milky Way as a stately disk, so large that it takes light 100,000 years to travel from one side to the other. Within this disk, the stars orbit the Milky Way's center; our Sun completes one orbit in about 225 to 250 million years. Look more closely, and stellar motion becomes more complicated, with the stars following individual orbits that can cross each other, bringing certain stars into close proximity now and then in (cosmically speaking) brief encounters.

These close encounters play an important role when it comes to cometary impacts on Earth. The solar system is believed to be surrounded by a gigantic cloud of small, icy bodies, namely comets. This "Oort cloud" is a roughly spherical shell extending from 2000 to 50,000 times the Earth-Sun distance from the Sun, so its outer edge is about one light-year from the Sun. There are likely to be billions of these comets with sizes up to a few or even a few dozen kilometers.

Given their great distance, these comets feel only a very slight pull of the Sun's gravity; only just enough to keep them in an orbit about the Sun. Thus, the gravity of a star that passes within a few light-years of the Sun can be strong enough to deflect them markedly from their original paths. The amount of deflection depends not only on how close the star passes, but also on how massive it is and how fast it is moving.

From encounters to collisions

Some of the comets can be deflected in a way that carries them into the inner Solar System. As they approach the inner regions, the Sun's light as well as its particle winds will strip material from the icy object, creating the distinctive long tail of a comet. After its closest approach to the Sun, the comet will head back out towards the Oort cloud, ready to repeat its orbit as long as it remains intact. In a few, rare cases, a comet could instead collide with a body in the inner solar system.

The existence of the Oort cloud and occasional disturbances are thought to be the explanation for long-periodic comets, whose journey around the Sun takes between 200 and thousands of years per orbit. In fact, the gigantic size of these comets' orbits, as inferred from observations of their passage through the inner solar system, was the motivation for postulating the existence of the Oort cloud in the first place. What we know so far about long-period comets supports this hypothesis, even though the Oort cloud has not yet been observed directly.

Thus, there is a direct connection between close encounters with stars and comet impacts on Earth, and to understand the latter, you need to research the former: How often do close stellar encounters occur? What encounters have there been in the past, how

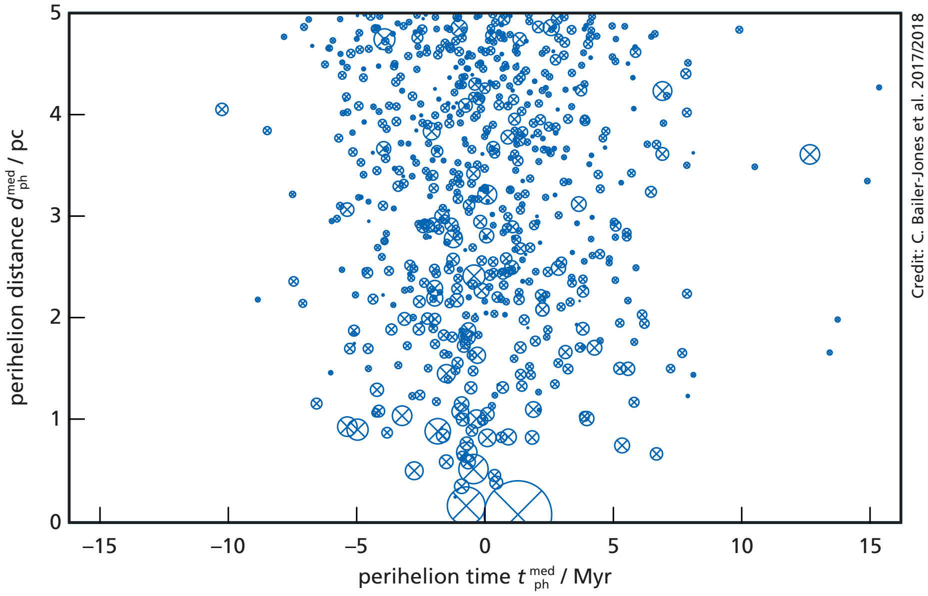


Fig. II.8.3: Same plot of distances over time as in Fig. II.8.2, but now each symbol is a circle whose area is proportional to the momentum transferred from the star to the Oort cloud.

have they influenced the frequency of impact events, and do they have a bearing on our estimates for the present?

Reconstructing stellar motions and close encounters

Answers to these questions depend crucially on the available data for stellar motion in our direct cosmic neighborhood, and in particular on how precise those data are. Coryn Bailer-Jones, a staff scientist at the Max Planck Institute for Astronomy, has published the first systematic estimate of the probability for such near stellar encounters. Bailer-Jones' calculations are based on the first data release (DR1) from the ESA astrometry satellite Gaia, which was published on 14 September 2016.

Gaia's mission is to measure the position, distance, and velocity of over one billion stars in our Galaxy, with an accuracy which has never before been achieved for so many stars. The final results will contain precisely what is needed to describe the orbits of stars in our galactic neighborhood: where these stars are in the surrounding space, and in which direction they are moving.

While the full reduction and analysis of the Gaia data is still in progress, DR1 published preliminary results on a special data subset that goes at least part of the way. This is the so-called TGAS catalogue of 2,057,050 stars, which makes use of both the first Gaia data and the data of the ESA-satellite Hipparcos, twenty years earlier, to yield the best stellar distances and motions to date.

Using this catalogue, Bailer-Jones identified 468 stars that, at their current rate of movement, would seem to come within 32.6 light-years (10 parsec) of the Sun, either in the past or in the future. For these stars he performed a computer simulation of their orbits – taking into account the gravity of our home galaxy – to determine more precisely their closest approach to the Sun. He found that 16 stars will pass, or have already passed within less than 6.5 light-years (2 parsec) of the Sun. (The light-year values are not round numbers since Bailer-Jones chose his sample values to be round in another distance unit used by astronomers, 1 parsec = 3.26 light-years.)

The closest future encounter

The closest encounter found is for the star Gl 710 ('Gliese 710'), which has been known for some time to be heading for a close encounter with the Sun. The new data and calculations show that this encounter, which will take place in 1.3 million years, comes much closer than was thought before DR1: just a quarter of a light-year (or 16,000 times the Earth-Sun distance), well within the Oort cloud. This confirms similar calculations by two Polish astronomers, Filip Berski and Piotr Dybczyński, in a 2016 article, also based on the first Gaia data release. Although Gl 710 has a comparatively low mass, just 60% the mass of the Sun, its velocity is also low, giving it plenty of time for exerting its gravitational influence on the Oort cloud. Given that Gl 710 may bring its own Oort cloud, this raises the intriguing possibility that our Sun could even swap comets with passing stars!

Deriving the rate of encounters

But beyond identifying the closest encounters, Bailer-Jones went an important step further. Astronomical surveys are never complete; they will only detect their

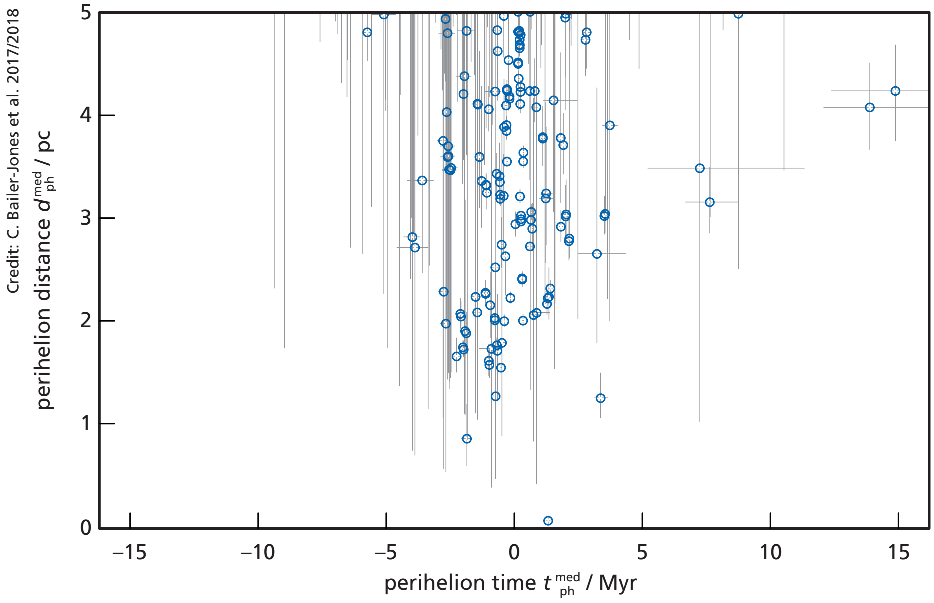


Fig. II.8.4: As Figure II.8.1, but based only on the first Gaia data release. The differences illustrate nicely the progress from Gaia DR1 to DR2.

targets down to some minimal brightness, and miss light sources dimmer than that. Bailer-Jones modelled the encounters that DR1 detected, compared them to the survey's limitation, and used statistical tools to estimate how many stellar encounters his DR1-based evaluation was likely to have missed. In addition, Bailer-Jones took into account the uncertainties of the Gaia data, which are known from systematic studies by the Gaia team. For each star, he calculated not only the orbit corresponding to the nominal Gaia values for distance, position and motion, but the orbits for a whole swarm of virtual stars. The swarm represents the (sometimes large) uncertainties in the data – and hence the fact that, with a certain probability, the derived parameters for the encounter could be different from the nominal estimates. This gives a more reliable estimate than relying on the nominal data alone.

As a result, Bailer-Jones obtained the first systematic estimate of the average stellar encounter rate for the past and future 5 million years. (The model reconstruction is not accurate enough to extrapolate to encounters further in the past or future with the DR1 data.)

The result, which meshes with earlier, less systematic estimates, is that within each period of a million years, between 490 and 600 stars will pass the Sun within a distance of 16.3 light-years (5 parsec) or less. This covers stars of all masses, although the most common ones are low mass stars, like Gl 710. Within a smaller distance of 3.26 light-years (1 parsec), some 19 to 24 encounters are expected per million years. Given that it takes several million years for disturbances to abate, our Oort cloud seems to be in fairly constant upheaval, with no extended periods of calm in between.

Not quite to the dinosaurs

This is valuable information for the scientists attempting to calculate the rate of cometary impacts on Earth. Gaia's next data release – DR2, in April 2018 - should allow an extension of these reconstructions to 25 million years from the present. The release after that, DR3, will contain estimates of the masses and radii of the observed stars, based on the data from Gaia's on-board spectrometer. Bailer-Jones is, in fact, in charge of the group of Gaia data analysts tasked with deriving these and other astrophysical quantities from Gaia's huge treasure trove of measurements. Information about masses and radii will allow the astronomers to estimate how large the disturbances in the Oort cloud will be on average, allowing for more precise estimates of their consequences for the impact rate.

Extending the reconstructions further will be difficult; as the simulations reconstruct longer orbits, uncertainty about the mass distribution in the Milky Way becomes a major limiting factor (although the Gaia data themselves will help us improve knowledge of this). Astronomers in search of stars that might be responsible for sending a comet to Earth that, 66 million years ago, caused or at least hastened the demise of the dinosaurs, will need to know our home galaxy much better than we currently do.

Coryn Bailer-Jones

C. A. L. Bailer-Jones 2017: "The completeness-corrected rate of stellar encounters with the Sun from the first Gaia data release" in Astronomy & Astrophysics Vol. 609, article id. A8. DOI: 10.1051/0004-6361/201731453

II.9 Highlight

Bringing the building blocks of life down to Earth, from space

Astronomers from McMaster University and the Max Planck Institute for Astronomy have completed calculations that lead to a consistent scenario for the emergence of life on Earth, based on astronomical, geological, chemical and biological models. In this scenario, life forms a mere few hundred million years after Earth's surface was cool enough for liquid water; the essential building blocks for life were formed in space during the formation of the solar system, and delivered to warm little ponds on Earth by meteorites.

The origin of life on Earth is one of the fundamental questions of science. While we are far from a definite answer, several interesting possibilities have emerged over the past decades. One, worked out in more detail in the 1980s, is the role of an "RNA world". The genetic information of higher organisms is stored in the double helix of DNA molecules. But there are closely related molecules, RNA (ribonucleic acid), which play a prominent role in modern cells; notably, they catalyze certain chemical reactions, and are essential for ferrying genetic information around inside the cell, and for the cell to synthesize specific proteins (the "executive orders" of cell government) based on genetic information. For some viruses, storing genetic information does not involve DNA at all; instead, all the information is encoded in virus RNA.

Credit: B. K. D. Pearce

Fig. II.9.1: A warm little pond on present day Earth, on the Bumpass Hell trail in Lassen Volcanic National Park in California. The warm little ponds that are prime candidates for the birthplace of life on Earth probably looked somewhat similar.

DNA and RNA

The key building blocks of both RNA and DNA are the nucleotides – in both cases, the pattern within the long, long chain of nucleotides determines the information carried by DNA and RNA. For DNA, this is sometimes expressed as a string where each character stands for one of the four possible nucleobases that form the key part of each DNA nucleotide, A for adenine, C for cytosine, T for thymine, and G for guanine (CGATTCACGATTACA...). In RNA molecules, thymine is replaced by Uracil, U. Another difference: While DNA is commonly found as the well-known double-stranded helix, RNA is more versatile in appearance – most common are single strands of RNA, folded in on themselves in what sometimes can become rather complicated shapes.

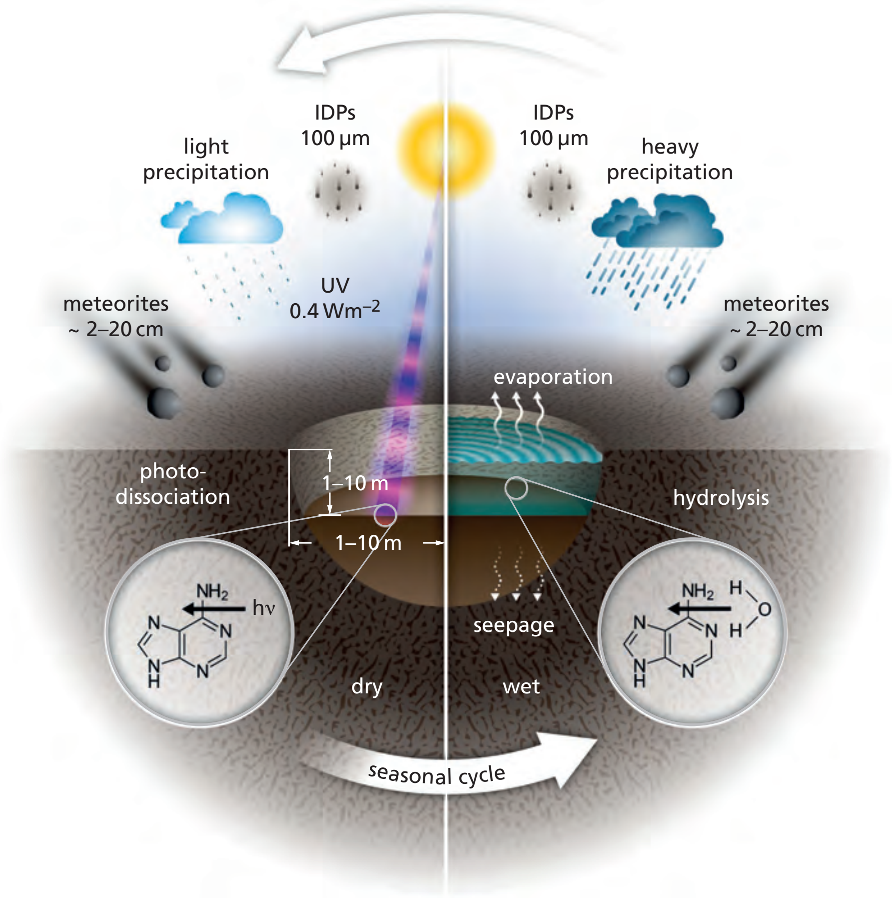
While RNA is essential for life as we know it, it also has several key properties that make it a good candidate for earlier, more primitive forms of life – before the advent of cells, to say nothing about multicellular organisms. The most important of these is the property to self-replicate – a given piece of RNA can gather the right nucleotides and arrange them into a copy of itself.

An early RNA world

The most promising current scenario for the emergence of life involves the formation of chains of nucleotides in the shape of RNA, self-replicating the emergence of simple cell precursors as fatty acids spontaneously self-assembled into membranes (a reaction that has been observed in the lab), forming primitive bag-like enclosures which allowed more complex chemical reactions to take place in their protected interior. From these simple beginnings, more complex mechanisms evolved, in particular those of DNA replication.

All the transitions of this scenario are, at this time, speculative, and for each step, alternative explanations and models exist – even for the notion of an RNA world preceding the DNA world, there are alternatives. But we live in exciting times, and there is a realistic hope that the next few decades will see a standard model for the origin of life established. Progress will require not just imaginative scenarios, but concrete calculations and experiments, showing which evolutionary pathways are feasible and which aren't. Advances involve different areas of research: On the one hand, more and more

Fig. II.9.2: A schematic representation of the various influences acting on chemicals in warm little ponds during the dry phase and wet phase of the cycle: infalling meteorites and interplanetary dust grains (IDGs), seepage, evaporation, re-filling through precipitation, hydrolysis of more complex molecules and photo-dissociation by UV photons from the Sun.



Credit: McMaster University

hypotheses about the transition from pre-life to life have become amenable to experimental tests, as our knowledge of molecular biology increases. On the other hand, there are exciting new developments at the interface of molecular biology and astronomy.

Over the past few decades, astronomers have made considerable progress in understanding how planetary systems form around young stars, and in particular about the evolution history of the Earth and our own solar system. The new results profit from the wave of exoplanet discoveries, and from direct observations of young planetary systems that have only become feasible with the advent of the most recent generation of telescopes. Planet formation models, including models of the evolving chemistry of newborn planetary systems, set the scene for the conditions under which life could have emerged four billion years ago in our own solar system, and how it could have formed in other planetary systems.

Combining astronomy, chemistry and biology

A study by the astronomers and planet formation specialists Ben Pearce, Ralph Pudritz, Dmitry Semenov and Thomas Henning is drawing together astronomy and prebiotic chemistry to shed light on the earliest era of the RNA world: the processes by which short RNA molecules band together to form longer molecules ("polymerization"), which then start to self-replicate in earnest in a later phase of chemical evolution.

Making longer RNA molecules is not easy, and requires certain well-defined conditions. One possible scenario locates the first steps towards life in the vicinity of hydrothermal vents in the deep ocean – fissures in the Earth's crust emitting water heated by the Earth's deeper, hotter layers. But there are questions about how longer polymers could form under these conditions; polymerization would seem to require a cycle of wet and dry conditions, unlikely to occur deep in the ocean. There is also the problem of obtaining a suitable supply of nitrogen in the shapes of molecules like hydrogen cyanide (HCN) or ammonia, necessary for forming the first stages of life as we know it.

Fig. II.9.3: Accumulation of the nucleobase adenine in a Warm Little Pond (WLP). The figure compares the two exogenous sources: Interplanetary Dust Particles (IDPs) and fragments of carbonaceous meteorites. The IDPs are micron-sized grains mainly originating from comets. The meteorite fragments are small (1 cm), and originate from a 40-m-radius carbonaceous meteoroid. Adenine concentrations for intermediate (wet–dry cycle) and wet environments (never dry) are compared and correspond to both a hot early Earth at 65 °C and a warm early Earth at 20 °C. The adenine concentration is much higher when it is brought to the WLP by meteorites because the extraction rate of adenine by water from a meteoritic porous body dominates over the adenine destruction by photodissociation and hydrolysis.

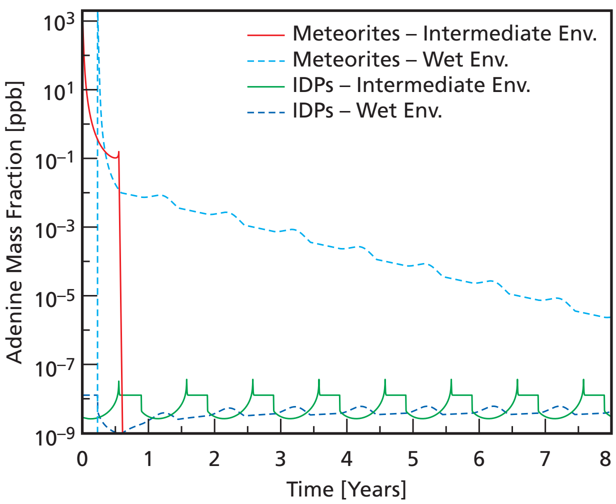
The appeal of warm little ponds

An attractive alternative as a likely birthplace of like are "warm little ponds": small, stagnant bodies of water, in which chemicals can concentrate, and react, under much more favorable conditions than in the ocean. Ponds with walls made of clay or other minerals create particularly favorable conditions, which would foster certain kinds of chemical reaction. An important feature of such ponds is the existence of wet-dry cycles. Every so often, such a pond would dry out, concentrating its chemical content even more and allowing bonding to occur between nucleotides. At some later date, the pond would re-fill with water. Such cycles very probably played a role in shaping the chemical reactions in such ponds. The phrase "warm little pond" itself goes back to one of the earliest speculations on the origin of life: an 1871 letter from Charles Darwin to the botanist Joseph Hooker.

Warm little ponds would have been comparatively rare four billion years ago, when oceans dominated Earth's surface even more than they do today, and when continents were just starting to rise, consisting mostly of igneous rocks created from the mantle, such as basalts. Violent volcanic eruptions were commonplace, and the atmosphere was dominated almost completely by volcanic gases. So where could the organic molecules have come from that set off the evolution of the RNA world?

Building blocks from outer space

A plausible answer, perhaps surprisingly, is that the building blocks for emergent life on Earth or similar planets could have come directly from outer space. The disks, made of gas and dust, that surround young stars contain considerable amounts of ammonia (NH_3) and hydrogen cyanide (HCN), both of which providing the nitrogen necessary for forming nucleobases. Iced-over dust particles in all but the innermost regions of such



Credit: B. K. D. Pearce et al. 2017

disks turn out to be surprisingly effective little chemical laboratories – in fact, experiments in a laboratory setting here on Earth show how molecules collecting on the icy surfaces of such dust grains can be processed into nucleobases when the grains are illuminated by UV light, such as would be the case for young stars.

In these experiments, scientists were able to show how three of the five nucleobases (namely uracil, cytosine, and thymine) formed spontaneously under such conditions. Meteorites are observed to contain considerable amounts of three of the five nucleobases (namely guanine, adenine, and uracil). It has been shown that these nucleobases are synthesized in the interiors of these meteorite's "parent bodies," namely large asteroids, during the formation of the solar system.

Meteorites and dust particles as a cosmic delivery service

Back to the warm little ponds – ideal environments for RNA molecules to become more complex, but where do the basic building blocks, the nucleobases in the pond, come from in the first place? The chemistry of the surrounding atmosphere, dominated by carbon dioxide (CO_2), nitrogen gas (N_2), sulfur dioxide (SO_2), and water (H_2O), is of no great help. Under the conditions on early Earth ("weakly reducing atmosphere"), even the occasional bout of lightning, as in the famous Miller-Urey experiment on the origins of organic molecules, will not produce a significant amount of nucleobases.

Meteorites falling on Earth, on the other hand, are a much more plausible source. At that time, roughly 4 billion years ago, meteoritic bombardment of Earth was between 100 million and 100 billion times more intense than nowadays, with between a trillion and a quadrillion kilograms of meteoritic material raining down on Earth's surface every year, carrying an estimated 2000 kilograms per year of carbon compounds that have survived the cosmic journey intact. In addition, there is a steady flow of interplanetary dust particles making their way to the surface of the Earth directly, carrying along whatever surface chemicals have formed. This much less spectacular arrival is nonetheless quite effective, amounting to an estimated 60 million kilograms of intact carbon compounds per year.

Meteorites seeding warm little ponds: a quantitative study

It's all very well to talk about a scenario such as meteorites or dust particles carrying nucleobases into small ponds, but unless the model is backed by quantitative data, it does not have much more explanatory power than a Just-So Story.

Pearce and his colleagues calculated a detailed model for this scenario. From a reconstructed history of the Moon's impact craters, they derived three possible scenarios for meteoritic bombardments of the Earth – a late bombardment model, with a late onset of intense meteoritic bombardment at about 3.9 billion years before the present, plus two additional models, both setting in around 4.5 billion years before the present, and representing the minimum and maximum amount of meteoric material compatible with the data, respectively.

They then calculated the probability of sizeable carbon-containing (carbonaceous) meteorites "seeding" these ponds. Specifically, these meteorites, which are originally between about 20 and 40 meter in diameter, break up into small pieces as they traverse Earth's atmosphere. The astronomers calculated the probability of such small pieces landing near a suitably sized warm little pond on Earth (between 1 and 10 meter in diameter), close enough for some of its organic material to enter the pond. (For this calculation, they had to estimate the number of warm little ponds; they did so by assuming a similar prevalence of ponds on landmasses as today, and accounting for the overall smaller landmass area back then, based on models of geological evolution. To be on the safe side, they repeated their calculation both for ten times as many and for one tenth as many ponds.) The result is that thousands of wet little ponds would have been seeded in this way, providing them with building blocks for emergent life.

Simulating what happens in warm little ponds

What happens to the meteorite- or dust-born nucleobases once they have entered the pond? A number of them will be lost: While the pond is filled with water, during one of the wet phases, nucleobases will be dissolved in water (hydrolysis). Some of the water will seep through pores in the basalt base of the pond, taking nucleobases with it, and removing those nucleobases from any further chemical reactions within the pond. During the dry phases, when the pond is dried up and its chemicals deposited as sediments, UV radiation from the Sun will split nucleobases into simpler compounds (photo-disssociation) – unless these nucleobases are protected by sediments on top.

With new nucleobases introduced into ponds at a certain rate, and with various mechanisms for nucleobase loss, it is quite clear that only quantitative modeling can tell whether or not there remained sufficiently many nucleobases in a number of ponds for longer chains of RNA to form. Again, the researchers considered several possibilities for dryer and wetter, hotter and colder conditions on the early Earth. These conditions will also determine how fast or slow nucleobases group together to form RNA chains.

Building block delivery: meteors, not dust grains

The first interesting result to come out of the study is that meteors, not interplanetary dust grains are the main source for nucleobases that survive the various adverse conditions. The reason is simply that the steady deposition by dust grains competes directly with the mechanisms for nucleobase loss, such as seepage and photo-dissociation. Meteorites, on the other hand, will deposit a considerable amount of nucleobases in one go, leading to higher nucleobase concentrations at least for a shorter time.

But, as it turns out, that shorter time is enough for the nucleobases to form longer RNA molecules, and those, in turn, are not lost as readily as their shorter kin. In particular, these larger molecules do not seep away through basalt pores, due to their larger size. That is how longer RNA molecules, once formed, can survive to take part in more complex chemical reactions – and why this happens on the basis of the nucleobases deposited in bulk by meteorites, but not with the steady stream of nucleobases deposited by interplanetary dust particles.

The case for quickly forming life

The deposition model has interesting implications for the timing of the origin of life. Over time, the meteorite infall rate quickly decreases, so there is a comparatively short window of opportunity. Most of the nucleobase delivery by meteorites must have occurred rather early, until about 4.17 billion years before our time. This suggests that the RNA world should have formed rather early, as well, namely 200 to 300 million years after the surface of the Earth had cooled sufficiently to become habitable – that is, after the temperatures had dropped sufficiently for areas of liquid water, such as oceans and lakes, to form on Earth surface.

Again, we are probably a few years off finding a complete, consistent, generally accepted model of how life originated on Earth. The calculation published by Pearce and his colleagues is one piece of the puzzle – demonstrating that meteorites are likely to play a major role in bringing the building blocks of life to Earth, and that under those circumstances, longer RNA pieces would have formed comparatively early in Earth's history. Overall, the calculations increase the feasibility of the warm little pond scenario, strengthening that scenario's position in comparison with the competing hydrothermal vent scenario.

But on the path towards a standard model, we need quantitative analyses such as the one described here – calculations that combine our knowledge about the geology of the early Earth, chemical conditions, properties of the molecules involved, and astronomical information about the properties of meteorites and interplanetary dust, to tell us which of the hypothetical steps from simple chemicals to self-reproducing living cells are feasible and which aren't. It is an exciting feature of current research on the origins of life that thanks to advances in many fields, from microbiology to the search for exoplanets and observations of planetary birthplaces around stars, we are steadily moving away from speculations and into the realm of quantitative analyses.

The work by Pearce and colleagues marks an important step on that journey – an achievement that the Proceedings of the National Academy of the United States of America honoured with the 2017 Cozzarelli Prize, awarded each year to six papers published in the journal which "reflect scientific excellence and originality."

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with

Ben K. D. Pearce (first author; McMaster University)

B. K. D. Pearce et al. 2017: "Origin of the RNA World: The Fate of Nucleobases in Warm Little Ponds" in the Proceedings of the National Academy of the United States of America, vol. 114, pp.11327-11332. DOI: 10.1073/pnas.1710339114

II.10 Highlight

Astronomers discover unusual spindle-like galaxies

Galaxies are majestic, rotating wheels of stars? Not in the case of the spindle-like galaxies studied by Athanasia Tsatsi and her colleagues. Using the CALIFA survey, the astronomers found that these slender galaxies, which rotate along their longest axis, are much more common than previously thought. The new data allowed the astronomers to create a model for how these unusual galaxies probably formed, namely out of a special kind of merger of two spiral galaxies.

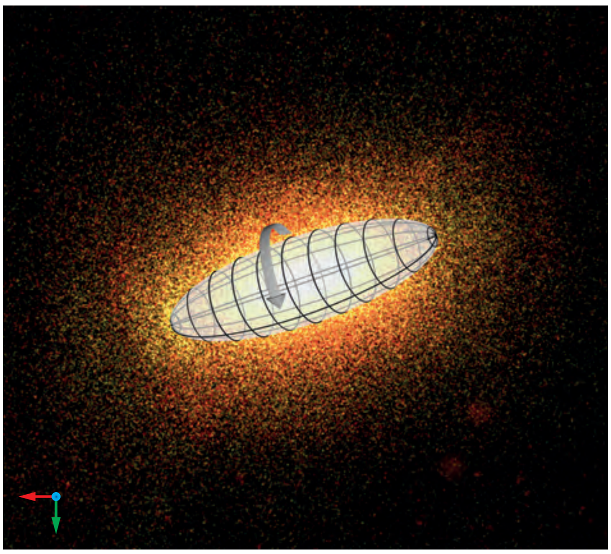
When most people think of galaxies, they think of majestic spiral galaxies like that of our home galaxy, the Milky Way: billions of stars, rotating in a flat disk similar to the way that a wheel rotates around its central axis. But while such disk galaxies are indeed common, accounting for roughly 70 % of all known galaxies in the nearby universe, some stellar systems are completely different. Notably, in so-called elliptical galaxies, stellar orbits are much more disorderly. Plot the stellar orbits in an elliptical galaxy, and the result will be similar to the external appearance of a ball of wool, with orbits oriented every which way.

Still, at least for most elliptical galaxies, this multitude of orbits follows an overall familiar trend: The vast majority of these galaxies are flattened in the direction of their rotation axis, as if pulled outward by centrifugal forces, resulting in a shape similar to that of a lentil. In these cases, there is at least some kinship with the wheel-like rotation of disk galaxies.

Spindle-like galaxies

But now, a group of astronomers led by Athanasia Tsatsi of the Max Planck Institute for Astronomy (MPIA) has found eight unusual galaxies whose overall shape resembles that of a cigar rotating along its longest axis; the technical term for such a shape is “prolate”. Astronomers had known about “prolate rotators” like this for a while, but had considered them comparatively rare. The new observations, which were carried out in the context of the CALIFA survey of galaxies, almost double the number of known prolate rotators, from 12 to 20, in one go – demonstrating clearly that this kind of galaxy is much more common than previously thought – they seem to amount to almost 1/10 of elliptical galaxies. Surprisingly, when looking at the most massive of all elliptical galaxies, they found that a third of them showed prolate rotation!

Six of the prolate rotators that had been known before the present study had been examined more closely using a technique known as integral field spectroscopy (IFS). An IFS observation provides spectra of numerous different parts of the galaxy, which contain far more information than a galaxy’s overall spectrum. The spectrum of a star – the rainbow-like decomposition of the star’s light into numerous different colors, corresponding to different wavelength regions – contains well-defined dark lines, known as absorption lines; for some stars, there are also bright lines, called emission lines.



Credit: J. Chang (PMO) / T. Müller (HdA)

Spectra show motion patterns

When a star is moving towards us, its lines are shifted towards smaller wavelengths (“blueshift”), when it is moving away from us, towards longer wavelengths (“redshift”), in what is known as the Doppler effect. If the spectrum covers a whole region within a galaxy, corresponding to many thousands of stars, lines will appear both shifted (representing the overall motion of that region towards us or away from us) and broadened (representing stars moving towards us and away from us

Fig. II.10.1: An elliptical galaxy in prolate rotation. The galaxy resembles the shape of a cigar, with its stars rotating around the galaxy’s long axis, similar to a spindle. The background image is a snapshot of a simulation by A. Tsatsi and colleagues.

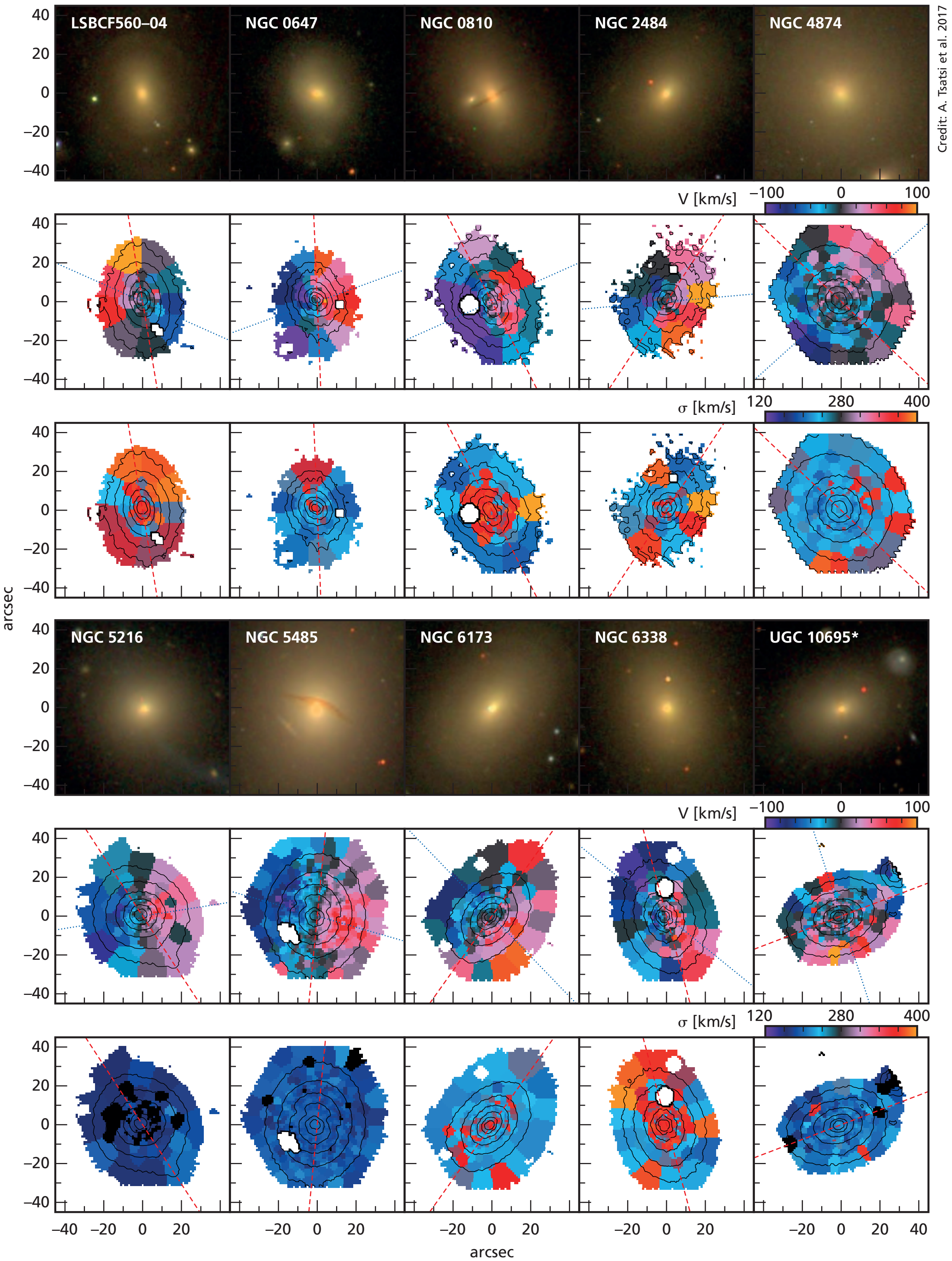


Fig. II.10.2: The CALIFA sample of prolate rotators. In each panel, the top row shows a color-composite SDSS image of each galaxy. The second row shows the speed at which different regions of the galaxy are moving directly towards us (blue) or away from us (red). The third row shows the degree to which the stars' motion in each region is disordered (that is, it shows the velocity dispersion). The top panel shows the galaxies LSBCF 560-04, NGC 0647, NGC 0810, NGC 2484, and NGC 4874. The bottom panel shows the galaxies NGC 5216, NGC 5485, NGC 6173, NGC 6338, and UGC 10695.

Credit: A. Tsatsi et al. 2017

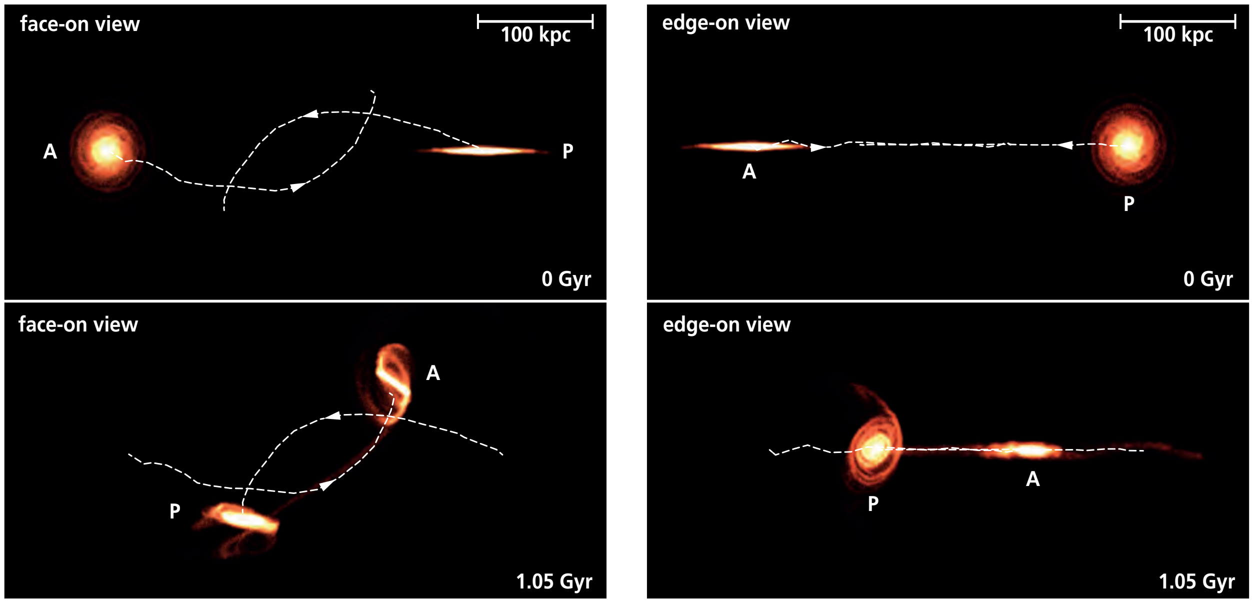


Fig. II.10.3: Face-on and edge-on projection of the orbital plane of a merger simulation showing the formation of a prolate rotator. The aligned progenitor is denoted "A", while the polar progenitor is denoted "P". The panels on the left show the initial setup before the merger simulation starts (t = 0). The panels on the right show the two progenitors 1.05 billion years later, at their first apocenter, where the aligned progenitor A has developed a strong tidally induced bar (seen face-on in the top right panel), while this is not the case for the polar progenitor P (seen face-on in the bottom right panel). The merger trajectories of the two progenitors are overplotted. The images were created with glnemo2.

in the region that was observed). In this way, an integral field spectrum contains information about the patterns of motion within the galaxy. Typically, astronomers will try to extract that information by simulating a variety of cases of stellar motion in such a galaxy, and then comparing with the IFS data to see which pattern of motion fits the observational data best.

Rare spindles?

Out of the thousands of galaxies astronomers have studied in the last six decades, only about 12 elliptical galaxies with prolate rotation have been identified so far – and out of these 12 galaxies, only six have been studied with integral field spectroscopy. With such low statistics, no clear indication of how this type of galaxies may have come about, and until now they were considered extremely rare objects.

Enter the CALIFA survey, carried out at the Calar Alto Observatory in Spain from 2010 onwards. The survey uses the IFS instrument PMAS mounted at the Calar Alto Observatory's 3.5 metre telescope, which uses 350 optical fibres to guide light from a corresponding number of different regions of a galaxy image into a spectrograph. For the CALIFA survey, more than 900 galaxies in the local Universe, namely at distances between 70 and 400 million light years from the Milky Way, were selected from the northern sky to fully fit into the field-of-view of PMAS. They include all possible types, from roundish elliptical to majestic spiral galaxies, similar to our own Milky Way and the Andromeda galaxy. In total, more than 600 of these pre-selected galaxies were observed in depth, yielding a rich data set of galaxy details.

In that data set, Tsatsi and her colleagues found the eight new cigar-shaped prolate rotators, plus one further galaxy with some evidence for prolate rotation which the astronomers classified as a candidate, plus one galaxy whose prolate rotation had already been known and was now confirmed. The CALIFA observation plan meant that for all ten of these galaxies, they had high-quality IFS data, giving insight into stellar motion patterns of all these galaxies. With the new and old data combined, they could tackle the question of how these unusual rotation patterns could come about in the first place.

Merging galaxies

The general scenario for galaxies evolving into ever larger and ever more massive galaxies over time involves galaxy collisions and mergers. For instance, disk galaxies like our own Milky Way grow by repeatedly merging with much smaller galaxies, building up mass over billions of years. In fact, their spiral structure, which is a density pattern pulsating through the galactic disk, can be explained by the disturbances caused by such repeated encounters with smaller galaxies, as can the bars found in some galaxies: elongated structures in these galaxies' central regions, from which the spiral arms emerge.

When galaxy encounters involve two big and massive galaxies, the situation is different. In those cases, the typical result is an elliptical galaxy, with no clear remaining disk structure. If there is sufficient gas in the colliding galaxies, then as the galaxies spiral into each other, gas, and with it the stars, will be influenced by this galaxy-around-galaxy rotation ("conservation of angular momentum"), and the result will be a flat, rotating elliptical galaxy, of no interest to those hoping to explain the cigar-like prolate rotators.

Mergers without gas

Much more interesting is the case of galaxies that contain almost no amount of gas at all. In those "dry mergers", stellar orbits are decided on a more individual basis, depending on how stars are moving during the merger, not imposed by any bulk gas motion.

With the help of Jiang Chang, a former PhD student at the Max Planck Institute for Astronomy, and now at the Purple Mountain Observatory in China, the group simulated such dry mergers, looking for results that resembled the pattern of motion of their sample of prolate rotators. Their search was successful, and indeed yielded a candidate mechanism.

The mechanism in question involves what is called a polar merger: two disk galaxies, oriented at right angles, orbiting each other, their orbital plane aligned with the disk of one of the galaxies, and then merging. While the two disk galaxies can be very similar initially, the merger affects them rather differently: the galaxy whose disk is aligned with the orbital plane will develop a strong bar, while the galaxy whose disk is at right angles to the orbital plane will remain fairly undisturbed. As the galaxies merge, the bar-shape will become the cigar-like overall shape of the resulting galaxy, while the undisturbed disk sets the overall rotation along the long axis.

Comparison with the data indicated that the prolate rotators were very likely formed in this way about 10 billion years ago, when the Universe was less than half its present age. The most striking example for prolate rotation resulted when the merging galaxies were almost pure disk galaxies, with no so-called "bulge" of older stars whose orbits carry them markedly below or above the plane of rotation.

The results are an interesting piece of the puzzle, explaining a likely formation scenario for an unusual, but not all that uncommon type of galaxy. Tsatsi's team of researchers having put to good use all the information contained in the CALIFA spectra, the ball is now in the court of the observing astronomers again: the merger simulations make some additional predictions for the detailed properties of prolate rotators, which cannot be distinguished with current observations, but could be tested with instruments like MUSE, the Multi Unit Spectral Explorer at ESO's Very Large Telescope, an 8 meter telescope at Paranal Observatory in Chile.

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A. Tsatsi 2017: "CALIFA reveals prolate rotation in massive early-type galaxies: A polar galaxy merger origin?" in Astronomy & Astrophysics Vol. 606, article id. A62. DOI: 10.1051/0004-6361/201630218

II.11 Highlight

Traces of life on nearest exoplanets may be hidden in equatorial trap, study finds

Simulations show that the search for life on other planets may well be more difficult than previously assumed: On planets like Proxima b or TRAPPIST-1 d, unusual flow pattern could hide atmospheric ozone from telescopic observations. Ozone, which is a variety of oxygen, is seen as one of the possible tracers allowing for the detection of life on another planet from afar. The simulations have consequences for formulating the optimal strategy for searching for (oxygen-producing) life such as bacteria or plants on exoplanets.

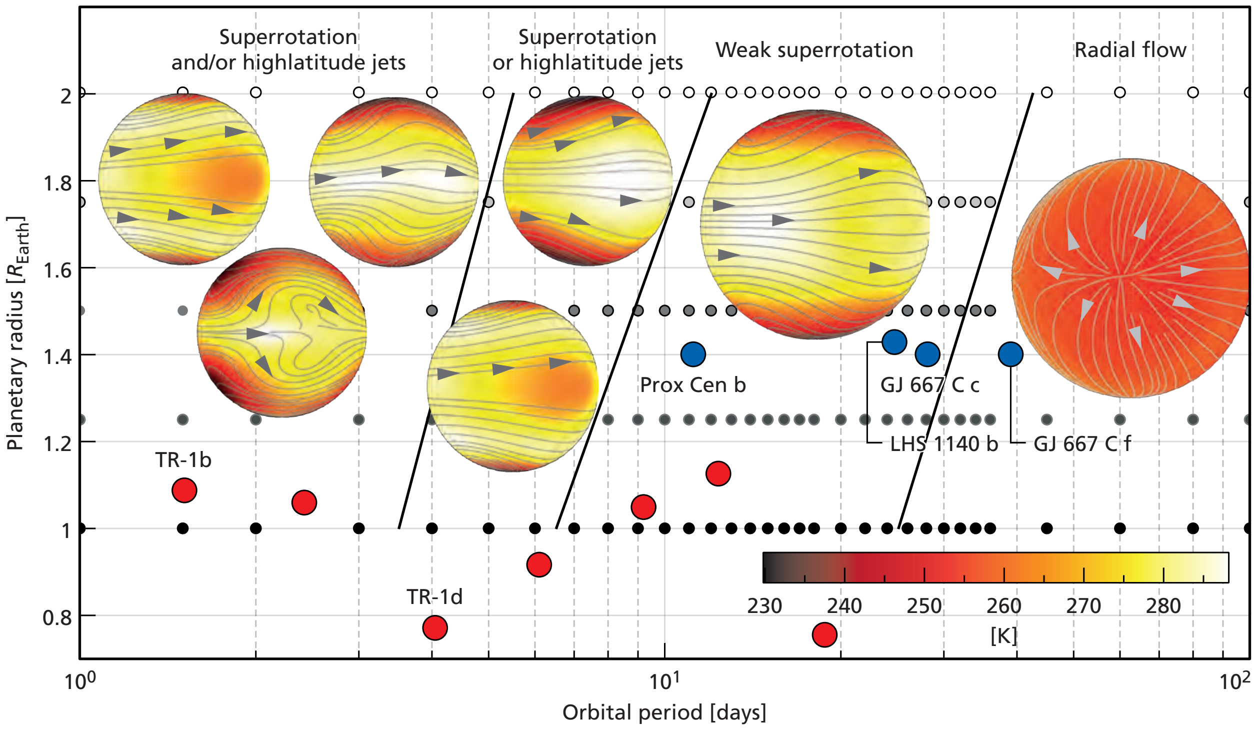
The search for exoplanets – planets orbiting stars other than the Sun – is one of the most fruitful areas of astronomical research over the past decades. It also promises answers to one of the most fundamental questions of science: are we alone in the Universe? Or is there other life out there?

With the next generations of telescopes, and improved observational techniques, answers to these questions might be forthcoming within the next few decades. Studies combining results from planetology, astronomy, atmospheric chemistry and biology have demonstrated a number of possibilities for tracing life on other planets via observations of exoplanet atmospheres. A recent study led by Ludmila Carone of the Max Planck Institute for Astronomy has shown that when it comes to the search for life in the Universe, matters are likely not as simple as had commonly been assumed.

Weather on other planets

The explanation involves concepts such as weather phenomena and jet streams that are familiar from ter-

Fig. II.11.1: Different troposphere circulation states identified in an earlier work by Carone, Keppens & Decin (2015) for tidally locked terrestrial planets with respect to orbital period and planetary size, assuming Earth-like atmosphere and thermal forcing. Example planets show a cross-section of the planet's temperature (colour) and wind flow (grey lines and black arrows) at the top of the troposphere $p = 225$ mbar and facing the substellar point. Red circles denote the radius and orbital period of the TRAPPIST-1 b,c,d,e,f,g,h planets in this "circulation state map" from left to right. Blue circles denote the position of Proxima Centauri b, LHS 1440 b, GJ 667 Cc and f, assuming Earth-like density for non-transiting planets. The black to white small circles denote the 3D climate simulations carried out in an earlier work by Carone et al. (2015).



Credit: L. Carone et al. 2018

restrial meteorology, but have only recently come to be included in realistic models of exoplanets – and it turns out to be particularly important for a number of Earth-like exoplanet candidates that are rather close to our own Solar System, and thus the natural first candidates for in-depth observations in search of life: Proxima Centauri b, whose discovery was announced in August 2016, and the planets of the TRAPPIST-1 system, announced in early 2017. In the TRAPPIST-1 system, Carone and her colleagues focused on TRAPPIST-1 d in particular, as the most promising potentially habitable planet of the system. For comparison purposes, the researchers also applied their models to two other objects: the planet TRAPPIST-1 b and the planet candidate GJ 667 Cf.

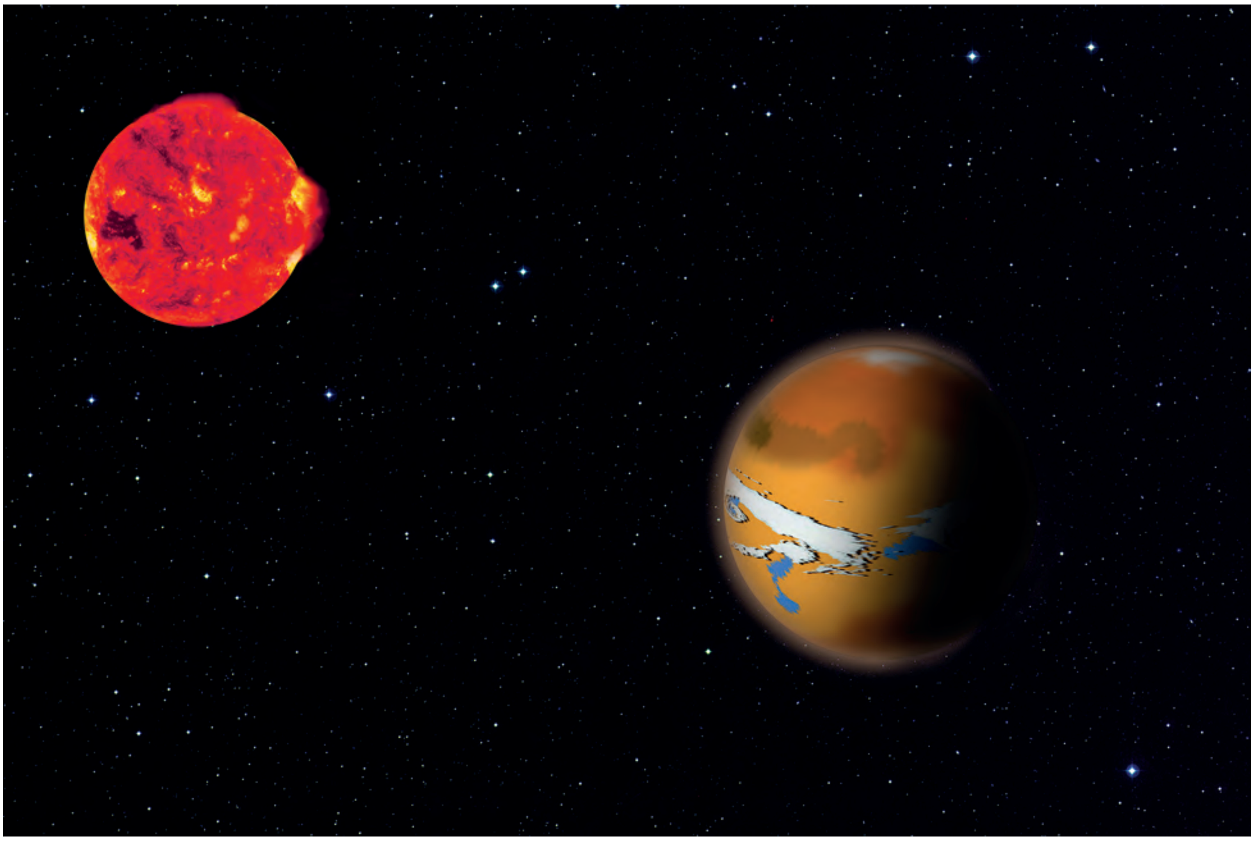
In the observation plans for the search for life on other planets, oxygen plays a key role. Oxygen is highly reactive; in chemical equilibrium, when chemical reactions have had sufficient time to run their course, one would expect oxygen to occur mostly in tightly bound molecules, having reacted with other elements, such as carbon, nitrogen, or various metals. But an alien astronomer studying Earth's atmosphere would find ample amounts of oxygen, and in particular of ozone, a particularly short-lived variation of oxygen (consisting of three oxygen atoms). And they would immediately ask why that should be so.

The ozone layer and life

Not only is the ozone layer, located in Earth's stratosphere at a height of between 20 and 30 kilometers above ground, an important protection for life on Earth, shielding as it does harmful ultraviolet radiation. It is also a direct consequence of the presence of life: Up until 2.45 billion years ago, Earth's atmosphere was practically devoid of oxygen molecules (O_2) and ozone (O_3). It was only through the rise of oxygen-producing cyanobacteria, which produce oxygen via photosynthesis like modern plants. Once the oxygen content was sufficiently high, ozone was produced in the atmosphere's higher layers, with UV light splitting oxygen molecules into oxygen atoms, and single oxygen atoms bonding with oxygen molecules O_2 to form ozone.

Since oxygen molecules are depleted as the oxygen reacts with other molecules in the atmosphere, an ozone layer will only be present if it is constantly replenished. On modern Earth, plants are responsible for this. Photosynthesis, by which plants produce energy-rich carbohydrates and molecular oxygen from carbon dioxide, water, and sunlight, ensures a steady supply of new oxygen molecules.

Fig. II.11.2: Artist's impression of TRAPPIST-1 d (*right*) and its host star TRAPPIST-1 (*left*). New research shows how planets like this could hide traces of life from astronomers's observations.



Credit: MPIA graphics department

Searching for life

In the search for life, oxygen and ozone are key players – although not the only ones. Typical search strategies combine various different telltale clues from the spectrum of an exoplanet atmosphere, such as oxygen, ozone, water, and methane, to ensure that a given chemical imbalance really indicates the presence of oxygen-producing life, and to exclude non-biological reactions that could be responsible for at least some atmospheric oxygen content.

So far, so good. But planetary atmospheres are not merely the locus of chemical reactions. Instead, atmospheres are in constant and complex motion, as we all know from everyday life, subject as we are to changing weather. Atmospheric dynamics turns out to be crucial for our atmosphere's ozone content, as well.

The ozone transport belt

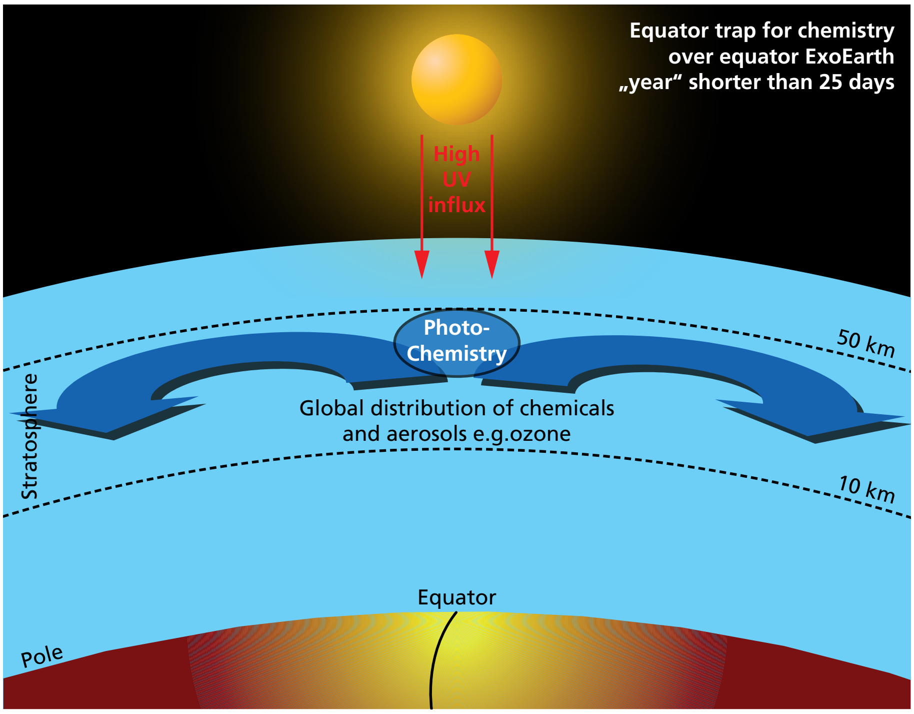
On Earth, most of the ozone is produced over the equator, where sunlight hits the atmosphere straight on, perpendicular to the atmosphere's layered structures. In regions far from the tropics, sunlight hits the atmosphere at more oblique angles, which makes for a less dense stream of photons and also means that photons have to traverse a larger portion of the higher atmospheric layers before reaching the stratosphere. Luckily for us, there is a large-scale flow, a gigantic "transport belt" for air which then carries most of the ozone in the direction of the poles. Also, Earth has seasons; as the Earth orbits around the Sun, either the Northern or the Southern hemisphere is tilted towards the Sun, receives a greater amount of sunlight and, in consequence, produces more ozone. Seasons and the transport belt are how Earth manages to have a global ozone shield, as opposed to a localized ozone concentration in the equatorial regions.

But this is also where it gets complicated for planets like Proxima Centauri b or the TRAPPIST–1 planets. All of these planets are very close to their respective stars: Proxima Centauri b is a mere 0.05 astronomical units from Proxima Centauri (the closest star to Earth), in other words: a mere 0.05 of the average Earth-Sun distance. The seven known planets in the TRAPPIST–1 system are between 0.01 and 0.06 astronomical units from their host star.

Such proximity almost inevitably leads to what astronomers call "bound rotation;" the planets themselves are said to be "tidally locked": At such close distances, the differences in gravity on a planet's far and near side are sufficiently great for this gravity to rotate the planet into a "preferred orientation"; in consequence, there will be one side of the planet that always faces the host star ("eternal day-side") and another side that always faces away from the star ("eternal night"). The same effect is at work in the Earth-Moon system; there, too, gravity is sufficiently strong for one side of the Moon to remain turned towards Earth, while the far side of the Moon remains invisible to an observer on Earth.

The potential perils of bound rotation

MPIA's Ludmila Carone is a specialist for exactly this kind of situation. A geophysicist by training, with a



Credit: L. Carone / MPIA graphics department

Fig. II.11.3: Earth's atmosphere has a "transportation belt" of air flows which move ozone from the main production areas near the equator towards the poles. This mechanism is important for creating Earth's global ozone layer.

background in astronomy and having run hundreds of three-dimensional climate simulations for various types of planets, Carone uses her unique skill set to investigate questions at the interface of astronomy, geophysics, chemistry and atmospheric physics.

When Proxima Centauri b and the potentially habitable planets in the TRAPPIST–1 system were discovered, Carone and her team turned their attention to these promising candidates for future observations. Building on previous work on large-scale flows in exoplanets that are in bound rotation, they tested various scenarios for these planets. Assuming the best, that is, assuming that these planets have atmospheres similar to Earth, would they also have a similar ozone layer that might be detected by future observations? What these planets definitely do not have is seasons, seeing that it is always the same hemisphere of the planet that is facing the star. But is there at least an "atmospheric transport belt" similar to that on Earth?

Crucially, Carone and her colleagues found that there is a likely complication. Some planets in bound rotation can indeed have an atmospheric transport belt, which carries air from the equatorial zones towards the poles. In that case, ozone produced near the equator would be distributed equally over the atmosphere, resulting in a global ozone layer. But there is another possibility: the "transport belt" could run in the exact opposite direction, towards the equator. In that case, what forms at the equator – such as ozone! – stays at the equator. Such a transport belt would essentially be a trap for chemical compounds such as ozone, confining them to a narrow portion of the planetary atmosphere.

The lengths of stellar years

In their simulations, the scientists found that the crucial factor to determine which scenario applies – trap or global distribution? – is the length of the planet's year, that is, the time it takes the planet to orbit its host star. Planets which take more than about 25 days for one full orbit around their star have ordinary, pole-wards transport belts, just like Earth. Planets with shorter orbits, such as Proxima Centauri b where one "year" takes a mere eleven days, are at risk of developing an equatorial trap.

But even those planets with a proper transport belt, running from the equator towards the poles, can face a potential problem, which literally lurks in the eternal darkness of the planet's night side. The pole-wards transport belt on the Earth-like exoplanets studied by Carone and her colleagues is generally much stronger and thus faster than on Earth.

When it comes to evenly distributing chemicals throughout the atmosphere, that can be too much of a good thing. In fact, overly strong pole-wards circulation might trap the planet's stratospheric ozone on the night side. For astronomers in search of life and, more concretely, in search of information about the chemical composition of the atmosphere, that is an unwelcome complication. These searches use spectroscopy, namely the rainbow-like decomposition of light into different color components to identify tell-tale signs ("spectral lines") characteristic for various atoms and molecules.

But for planets orbiting distant stars, spectral analysis is challenging. One method analyses infrared radiation from the planet's warmer day side. But this will, naturally, not find chemical compounds that occur only on the

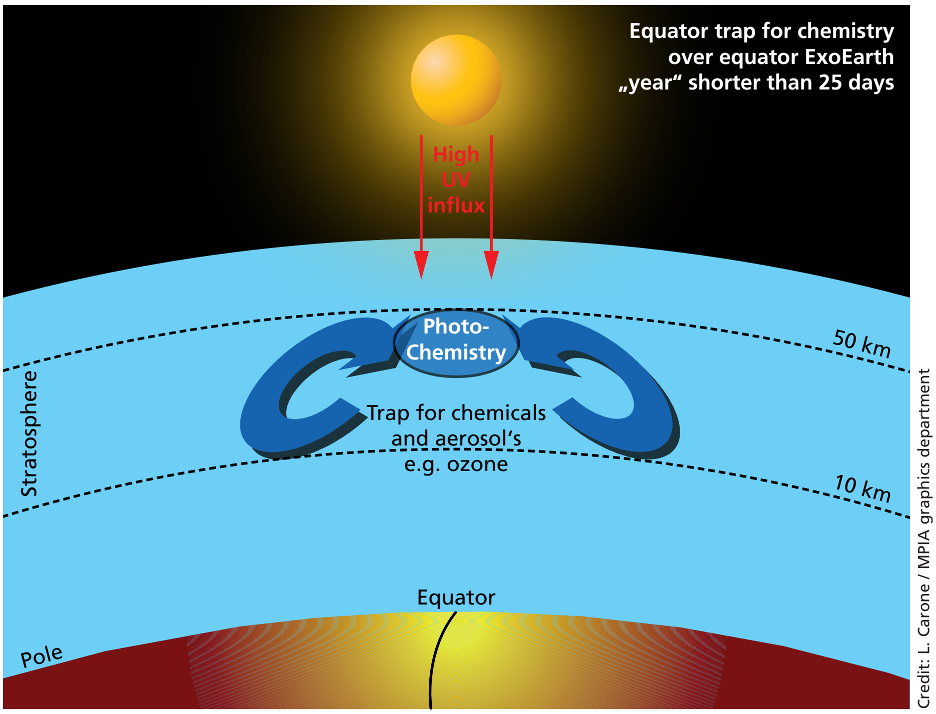


Fig. II.11.4: As a new study by Ludmila Carone shows, certain exoplanets could have air flows that serve to trap ozone in the equatorial regions. This could present an unforeseen complication for the search for traces of life on these planets.

night side. Another method can be applied to transiting planets, which, from the perspective of an observer on Earth, pass regularly in front of their host star. Once the planet is in front of the star, one can examine how the starlight is changed as it passes through the planet's (thin!) atmosphere. But this method only yields information about atmospheric regions near the day-night border, and can tell us nothing about compounds trapped deep in the night regions. In both cases, detection of chemical compounds that are confined to the night regions would be considerably more difficult than for compounds that are distributed evenly in the atmosphere.

Chances for life

Even without a global ozone layer, or even an ozone layer altogether, an Earth-like exoplanet like Proxima Centauri b or TRAPPIST-1 d might still be habitable. For one, these planets orbit comparatively cool, red stars, which emit very little harmful ultraviolet to begin with – although on the other hand, these stars can also be very temperamental, and prone to violent outbursts of harmful radiation that include such ultraviolet light. The jury is still out on what that means for the possibility of life.

For more definite results both on the habitability of Earth-like exoplanets without global ozone layers and about the detectability problems, both better observations and more complex models are needed. The former is likely to be provided by the James Webb Space Telescope (JWST), slated for launch in 2021. JWST is going to take infrared spectra with unprecedented accuracy, with higher resolution and over a larger range of wavelength than before. The infrared region is a part of the spectrum where molecules in the atmospheres of exoplanets, including ozone and methane, leave their most characteristic traces. That is why JWST can be expected to take the chemical analysis of exoplanet atmospheres to a whole new level.

Levels of complexity

Regarding the latter, more complex models, Carone and her colleagues are already hard at work. The study described here focuses on atmospheric dynamics, charting the various streams and "transport belts" and, more generally, air circulation in the atmospheres of exoplanets in bound rotation. This gives valuable indications about what to expect for the distribution of various chemicals, in particular ozone, in the atmospheres of these planets, but it does not include explicit modelling of those chemicals and their changing distributions. A more definite answer as to whether or not ozone might be playing "hide and seek" in the atmospheres of Proxima Centauri b and TRAPPIST-1 d will require simulations that include both atmospheric dynamics and the chemistry of compounds such as ozone, and Carone and her colleagues are in the process of running this kind of more complete simulation.

All in all, the present results sound a note of caution when it comes to the search for life in the atmospheres of exoplanets. After all, the apparent absence of ozone in such observations would not mean that there is no ozone, and oxygen-producing life at all. Alternatively, the ozone could be trapped out of sight, making a detection difficult. This would stress the importance of alternative markers of the presence of oxygen, such as molecular oxygen (O_2) itself and the highly unstable tetraoxygen (O_4), that would not be subject to the same difficulties as ozone. In addition, the possibility of hidden oxygen shows how important it is not to focus on a subset of markers, but instead to obtain a fuller picture of what is happening in the atmosphere. The prevalence of methane and water, direct measurements of the intensity of the ultraviolet light falling onto the atmosphere, and measurements of indicators that show atmospheric temperature and pressure: all these together would allow for a model of chemical reactions within the atmosphere that would show much more definitely whether biological activity is needed to explain the observations or not.

It is a truism that the search for signs of life on other planets is difficult. But as this new study shows, there might be some additional wrinkles to that difficulty – but, in the shape of atmospheric models, also new and promising directions in which the search for life outside Earth might make progress towards its ultimate goal.

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L. Carone et al. 2017: "Stratosphere circulation on tidally locked ExoEarths" in Monthly Notes of the Royal Astronomical Society Vol. 473, pp. 4672-4685. DOI: 10.1093/mnras/stx2732

II.12 Highlight

The most distant black hole in the cosmos: quasar at a distance of 13 billion light-years discovered

Astronomers have discovered the most distant quasar known, which is so far from us that its light has taken more than 13 billion years to reach us. We see this quasar as it was a mere 690 million years after the Big Bang, and its light carries valuable information about the early history of the Universe, in particular the reionization phase. At the center of the quasar is a massive black hole with a mass of almost 1 billion solar masses. In addition, the quasar's host galaxy has been found to contain a large amount of gas and dust, challenging models of galactic evolution.

Researchers have discovered the most distant active black hole yet known: a quasar so far away that its light has taken 13 billion years to reach us. Light from that quasar tells us about the properties of the Universe a mere 690 million (0.69 billion) years after the Big Bang.

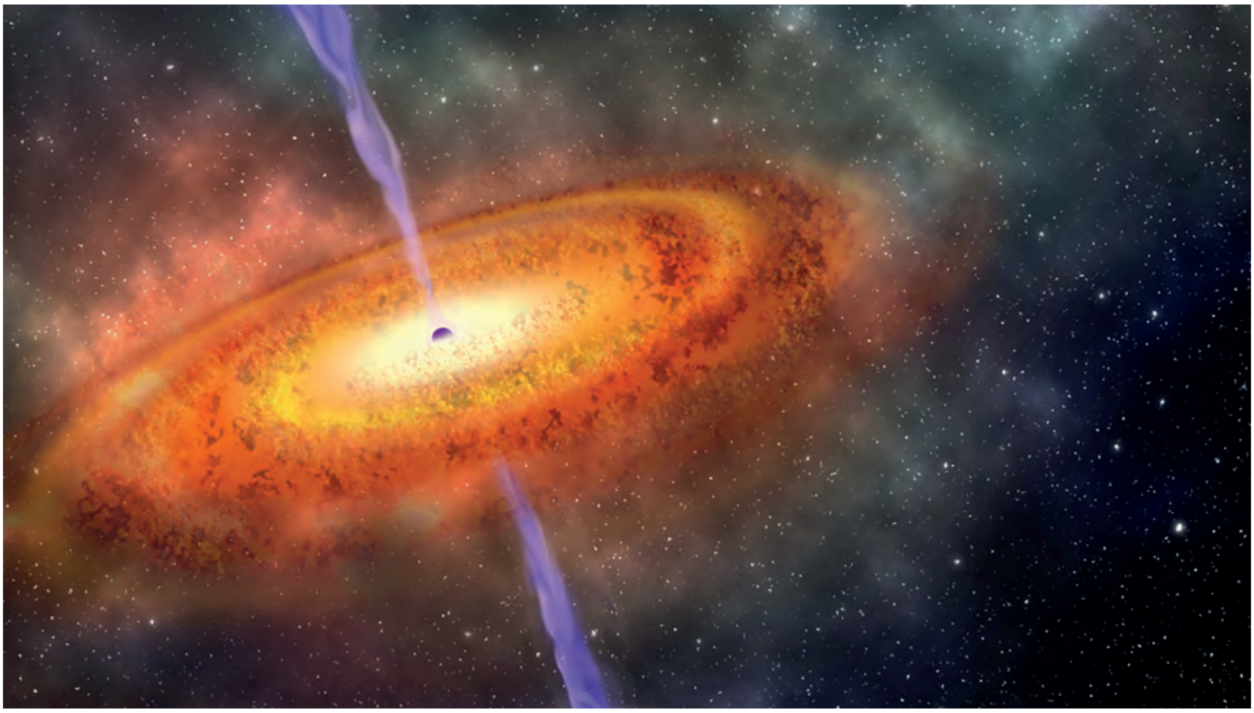
Fig. II.12.1: Artist's impression of a quasar: a supermassive black hole, surrounded by an accretion disk of material. Astronomers have found the most distant quasar yet known, and used it to obtain key information about the early Universe.

Quasars: extremely bright and incredibly distant

Quasars are exceedingly bright astronomical objects. They are the active nuclei of distant galaxies, and their light is produced when matter (such as gas, or even whole stars) spirals into a distant galaxy's central, supermassive black hole. Such matter collects in a so-called accretion disk around the black hole, reaching temperatures of up to a few hundred thousand degrees Celsius before finally falling into the black hole itself. The formation of quasars and their interactions with their host galaxies is an active area of study.

Typical quasars are as bright as a few trillion suns, and thus about ten times brighter than all the stars in our own galaxy combined. With such extreme luminosities, quasars are visible over large distances and are among the most distant astronomical objects we can observe.

For all these distant galaxies and quasars, their distance is typically determined making use of a systematic relation between distances and redshifts that follows directly from the models of cosmology. The redshift, concretely: How strongly the wavelengths of an object's light are shifted towards longer wavelengths by the expansion of the Universe, can be determined from



Credit: Carnegie Institution for Science the spectra of galaxies and quasars. Using the standard model of cosmology, those redshifts can be converted to distance values.

Because of this connection between the redshift z and the distance, very distant objects are also referred to as "high-z". For the newly discovered quasar, the distance value corresponds to a redshift of z = 7.5, meaning that its light reaches us at 7.5+1 = 8.5 times the wavelength at which it was originally emitted.

Probing the early Universe with quasars

Distant quasars are not just a matter of humans' fondness for records and extremes – they carry key information about the properties and evolution of the Universe! For one, quasar light can be used to "x-ray" the cosmos: Hydrogen atoms in the vast reaches of space between the distant quasar and the observer will absorb some of the light, and leave tell-tale signs of their presence in the spectrum of the quasar (that is, the rainbow-like composition of the quasar light into different wavelengths, or colors). In this way, quasars can be used to study the large-scale distribution of atomic intergalactic matter in the cosmos.

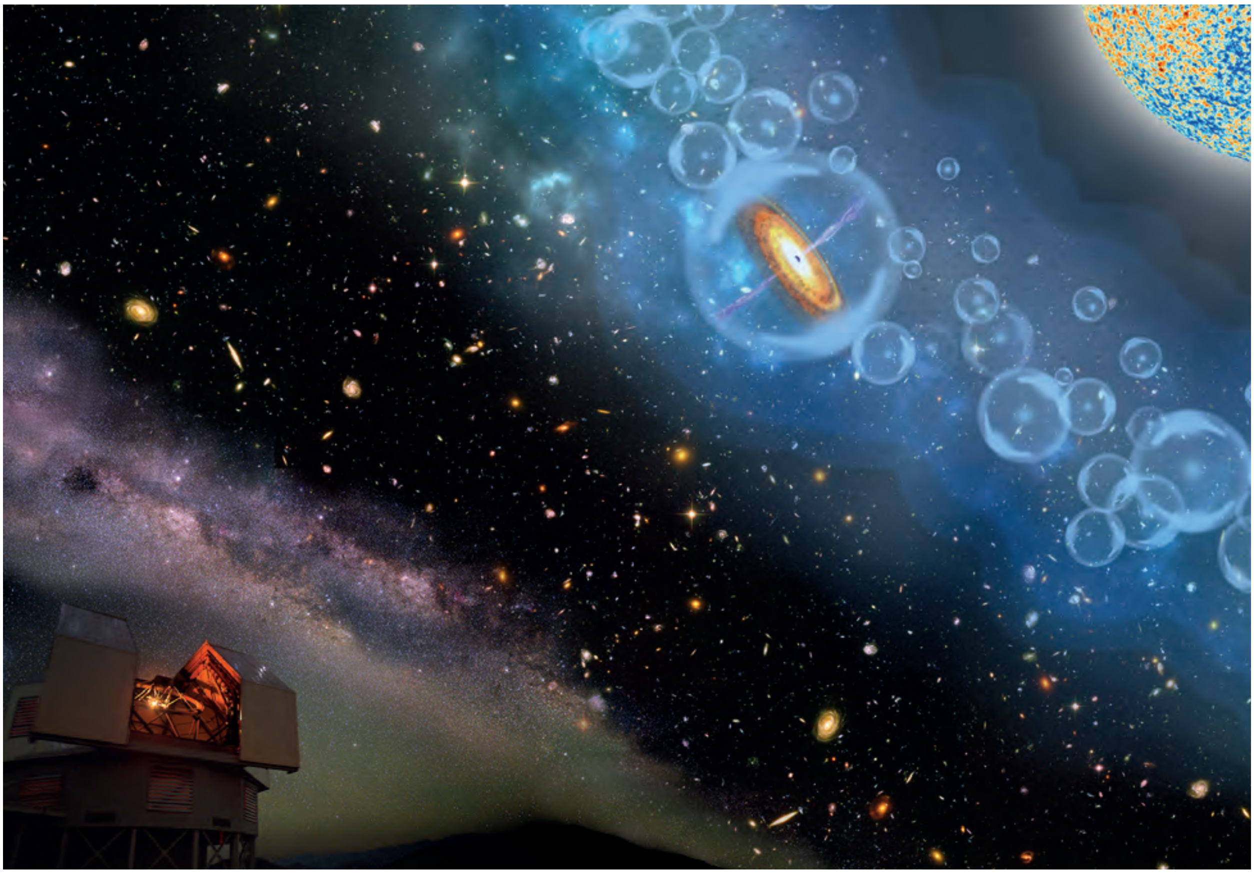
Such quasar-based studies of the distant large-scale Universe promise answers to some very fundamental questions. How, for instance, has the fraction of neutral hydrogen (as opposed to ionized hydrogen) changed in the early Universe? In the current models, ultraviolet radiation from the bright first stars and the accretion disks of the first black holes reionized the gas filling our Universe between 12.5 and 13.5 billion years ago, comparatively shortly after the Big Bang, stripping the electrons from most of the hydrogen atoms filling the cosmos back then. This cosmic reionization was a fundamental transition in the early Universe.

There are currently several competing models for how this transition happened, some favoring an earlier, some a late onset of the reionization. With distant quasars, one can hope to pinpoint this transition: By measuring the amount of neutral hydrogen atoms in the distant intergalactic medium, one can constrain the fraction of neutral and of ionized matter, and rule out at least some of these models.

Witnessing galaxy evolution

Distant quasars are also interesting in and of themselves. After all, the long light travel times mean that we see the

Fig. II.12.2: Schematic representation of the look back into history that is possible by the discovery of the most distant quasar yet known. The observation using one of the Magellan telescopes (*bottom left*) allows us to reconstruct information about the so-called reionization epoch ("bubbles" *top-half right*) that followed the Big Bang (*top right*).



Credit: Carnegie Institution for Science / MPIA graphics department most distant quasars as they were when the Universe was less than a billion years old. Research into the evolution of galaxies, of the central black holes of these galaxies and of the active phases when such a black hole becomes a quasar, is a highly active sub-field of cosmology. The evolution models currently under discussion make different predictions for the rate of black hole growth and of galaxy growth.

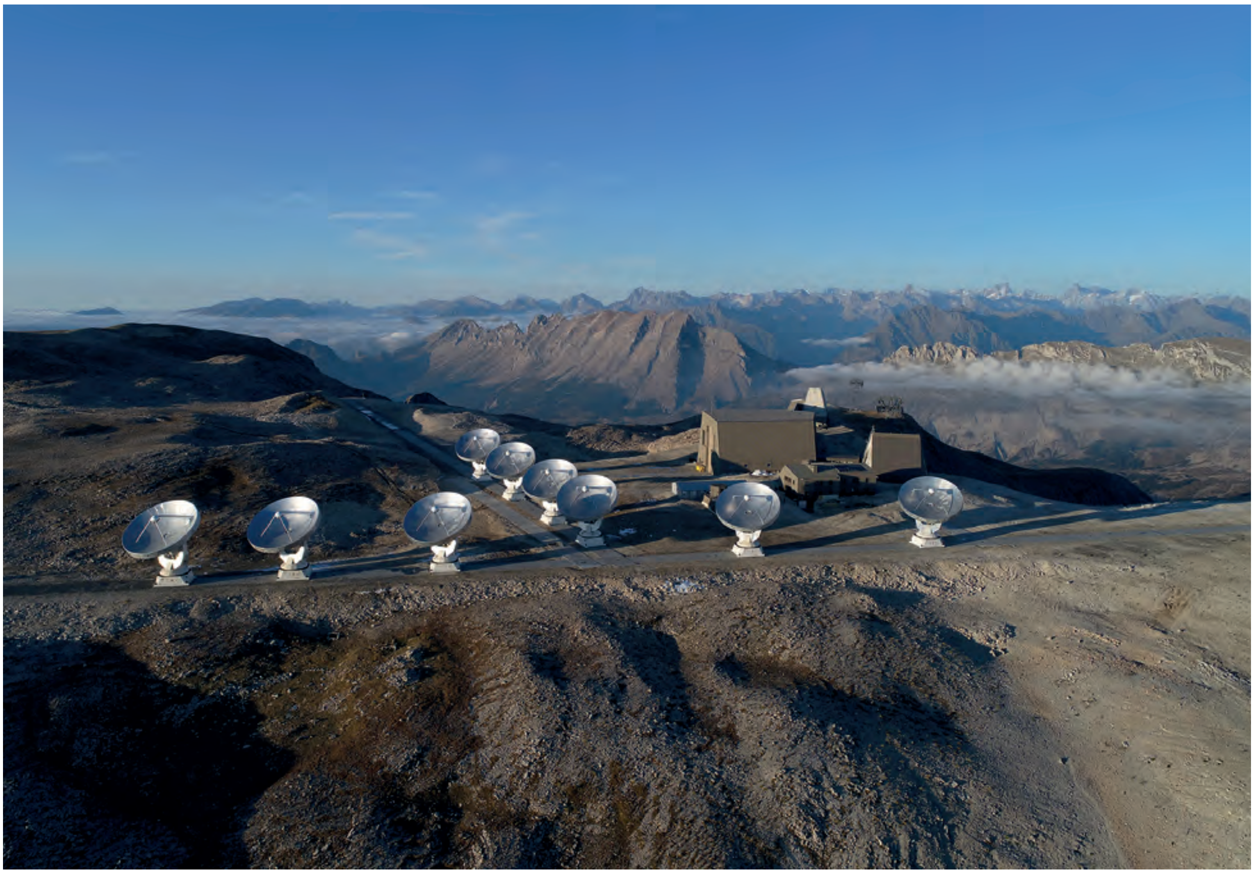
The more distant the quasar, the deeper we are peering into the past. Different models of how galaxies and their central black holes have grown over time make different prediction for the maximal possible masses of both galaxies and their central black holes for different times in cosmic history. By observing the most distant quasars, which we see as they were billions of years ago, we can put those models to the test. After all, we see each quasar as it was in some bygone cosmic era – if light from a certain quasar takes 13 billion years to reach us, we will see that quasar as it was 13 billion years ago. If the quasar's black hole mass back then was larger than the maximal mass predicted by a specific model, that would count as strong evidence against the model.

For these reasons, finding very distant quasars has been an important goal of observational astronomy for decades. Of particular interest are quasars that we see as they were during the first billion years of cosmic history (redshift $z > 6$). At least for the era between about 850 million and one billion years after the Big Bang, astronomers had found a few dozen of these quasars between 2000 and 2010: the Sloan Digital Sky Survey (SDSS), a systematic survey covering the northern hemisphere identified 20 quasars from that early period (redshift $6 < z < 6.5$), and the Canada-France High-z Quasar Survey found another 15, some of those in the southern hemisphere.

Systematic search for distant quasars

More distant quasars were harder to come by. In 2010 the group of Fabian Walter and Bram Venemans at the Max Planck Institute for Astronomy (MPIA) set out for a systematic search. The astronomers made use of large surveys, most notably the PanSTARRS1 survey to find the most distant quasars in the Universe. The Pan-STARRS1 survey (short for "Panoramic Survey Telescope & Rapid Response System 1") utilised a 1.8 meter telescope at the summit of Haleakalā, on Maui/Hawaii, to digitally map three quarters of the sky in visible and near infrared light. The survey took approximately four years to complete, and scanned the sky 12 times in five filters. Candidate objects that might be distant quasars were selected from the surveys, and

Fig. II.12.3: Antennas of the NOEMA array, at IRAM. NOEMA was used to examine the host galaxy of the newly discovered most distant quasar known to date.



Credit: Carnegie Institution for Science then observed more closely using various telescopes accessible to MPIA researchers through special agreements. Finding and characterizing the most distant quasars became the PhD thesis of Eduardo Bañados, then a graduate student at MPIA.

This search raised the number of known quasars with redshifts higher than $z = 6$ from dozens to about a hundred, with new finds in particular in the Southern hemisphere. An article describing the discovery and physical characterization of a sample of the most distant quasars was recently published by a current MPIA PhD student, Chiara Mazzucchelli.

A closer look at distant host galaxies

In parallel, members of Walter's group began to look at the newly discovered quasars in more detail. The stellar light of the host galaxies of these distant active galactic nuclei, radiating mostly in ultraviolet, visible light, and near infrared, are outshone by the powerful radiation of the quasar itself. On the other hand, at far infrared, submillimeter and millimeter radiation, and thus at much longer wavelengths, the host galaxy dominates the emission – so observations at these wavelengths are the method of choice when searching for host galaxies.

Via the Max Planck Society, MPIA has access to the NOEMA interferometer on Plateau de Bure in the French Alps, which combines several 15 meter antennas for millimeter radiation. For the quasars visible from the Southern hemisphere, the researchers used ALMA, a submillimeter/millimeter observatory in the Chilean Atacama desert. Using these telescopes, the astronomers were able to detect dust and gas emissions from the host galaxies of all of the quasars their systematic search had found.

These findings are important indicators of chemical evolution in the Universe. Right after the Big Bang, the only elements in the Universe were hydrogen (75 %, by mass) and helium (25 %). Pretty much all of elements heavier than helium we find the present-day Universe were produced in stars, over the course of the billions of years following the Big Bang. The host galaxy studies indicated, in line with earlier results, that there was already a substantial amount of these metals (as elements heavier than helium are called in astronomy) in galaxies about a billion years after the Big Bang.

Going to even greater distances

In all those areas, data from an even earlier phase of cosmic evolution promises additional interesting information – on galaxy evolution as well as on chemical evolution. That is why the scientists decided to push even further, and set their sight on quasars more than 12.9 billion light years away (redshift $z \geq 7$). At the start of their search, only one quasar in this distance range was known. It was 12.96 billion light years away; Bram Venemans at MPIA was the first astronomer to detect its host galaxy, using the IRAM Plateau de Bure interferometer.

The new search profited from the international element characteristic for successful scientific careers: when Bañados finished his PhD in 2015, he became a postdoctoral researcher at the Carnegie Institution for Science in the US, as a Carnegie-Princeton Fellow. Through his new institute, Bañados gained access to the Carnegie Institution's Magellan telescopes, two 6.5 meter telescopes at Las Campanas Observatory in Chile, significantly strengthening the observation powers of the quasar search.

The astronomers started this new stage of their search by looking at large-scale infrared surveys: the ALLWISE survey by NASA's WISE infrared space telescope, a large area survey by the United Kingdom Infrared Telescope (UKIRT) on Hawaii, and a survey by the Dark Energy Camera (DECam) at Cerro Tololo Inter-American Observatory in Chile. From the hundreds of millions of sources documented in these surveys' extensive catalogues, the astronomers selected several hundreds of quasar candidates. Those candidates were then observed more closely with numerous telescopes, including the Magellan telescopes.

Breaking the distance record

It was at this stage of the search that Bañados discovered the quasar J1342+0928 (whose designation, as is customary, is composed of coordinate values giving its position in the sky) using one of the Magellan telescopes. Astronomers had long been looking for a quasar as distant as this one. J1342+0928 broke all previous distance records for quasars in the early Universe. The discovery observations unambiguously showed that this quasar is at a redshift $z = 7.5$. This corresponds to a distance of 13.01 billion light years – light from that distant quasar took 13.01 billion years to reach us. The astronomers were seeing that quasar as it was a mere 690 million years after the Big Bang.

Further analysis showed that this was a comparatively bright quasar, emitting 40 trillion times as much energy per second as the sun. From estimates of the total quasar population, there should only between 10 and 100 quasars in total that are at least as distant and at least as bright as this one. A rare probe of the early Universe indeed!

From the properties of another spectral line, that of ionized magnesium (MgII), the astronomers derived a value of 800 million solar masses for the mass of the quasar's central black hole. This large mass poses a challenge to models of supermassive black hole formation in the early Universe. Such models would either need to show how there could have been "seed black holes"

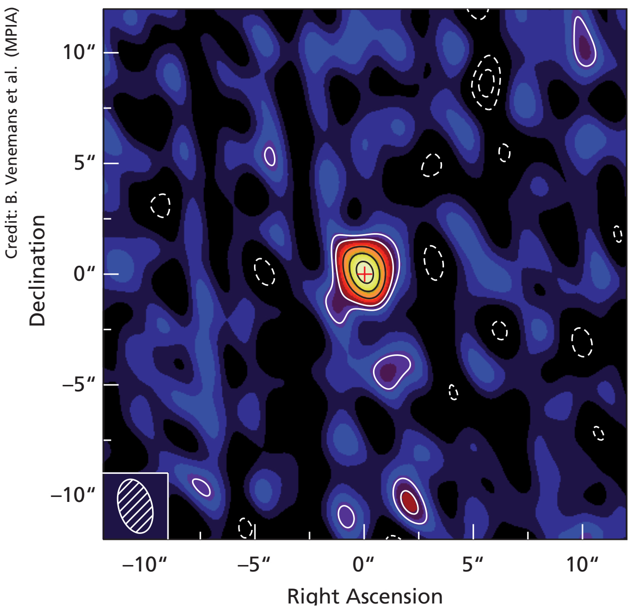


Fig. II.12.4: Image of the newly discovered quasar's host galaxy, taken in the characteristic light of ionized carbon, [CII]. Observations like this showed that the host galaxy contains surprising amounts of heavier elements and dust.

with masses of about 10,000 solar masses a mere 65 million years after the Big Bang, or they would need to demonstrate how the earliest black holes could grow more quickly than is commonly assumed (faster than the so-called Eddington limit).

Reionization happened rather late

The absorption features in the quasar light – traces of intergalactic material between the quasar and us – have another interesting consequence. Evidently, near the quasar, between 38 and 77 percent of intergalactic hydrogen were still in the form of atoms, and not yet ionized. The quasar observations give a glimpse of the reionization phase – and it provides evidence for those models where reionization sets in comparatively late in cosmic history.

When Bañados reported his exciting finding to his collaborators at MPIA, the astronomers acted quickly. Ordinarily, astronomers need to apply for time at large telescopes, a process that usually takes a few months. But for urgent observation requests, and to follow up quickly on new discoveries, most observatories have what is known as "Director's discretionary time" (DDT), which allows for a quick decision by an observatory director (or their representatives) to allocate observation time. The group at MPIA submitted DDT proposals both for the NOEMA interferometer and for the Extended VLA (EVLA) antenna field of the National Radio Astronomy Observatory in New Mexico.

The first NOEMA observations, with 8 antennas observing in unison, were undertaken mere days after Bañados had first discovered the quasar, analyzed at MPIA, and they showed clear traces of the quasar's host galaxy. Using the spectral lines of ionized carbon, commonly designated [C II], and the dust continuum, this analysis showed that the newly discovered quasar was very special indeed. The [C II] line also confirmed the quasar redshift of $z = 7.5$ (corresponding to all wavelengths of its light stretched by a factor 8.5 since they were emitted, as a direct consequence of cosmic expansion).

A precocious host galaxy

The quasar host galaxy itself is highly active. The observations indicate that it is forming between 90 and 600 solar masses worth of stars per year (compared with about a single solar mass per year in our home galaxy, the Milky Way). Equally important, the galaxy already contains copious amounts of metals (elements heavier than helium) and dust. The observations indicated the presence of about 100 million solar masses' worth of dust, and at least five million solar masses of carbon in the galaxy's interstellar medium.

All of these metals need to have been produced in massive stars, and spread throughout the interstellar medium by the supernova explosions that mark the end of such massive stars. The extreme brightness of the central accreting black hole makes it nearly impossible to directly detect the stellar light from the host galaxy. However, from the amount of dust and ionized carbon detected with the millimeter observations, the astronomers were able to estimate that the quasar host galaxy could contain stars with a total mass of 20 billion solar masses – quite a lot, compared with the total stellar mass of between 40 and 60 billion solar masses of the stars our own Milky Way galaxy at the present time.

In other words: In only 690 million years, the host galaxy of the newly discovered quasar had already formed about half of the stars that the Milky Way formed within several billion years! It should be mentioned, though, that there is considerable uncertainty attached to these calculations, and it is possible that the number of stars formed in the quasar host is considerably smaller. In that case, in order to get the considerable amount of metals revealed by the observations, most of the stars would need to have been very massive.

Not only was the quasar host galaxy producing copious amount of dust 690 million years after the Big Bang, at the stage shown by the observations – it must have been producing numerous stars, and the associated heavier elements, in the millions of years before that! This puts strong constraints on models of galaxy evolution.

Future plans

The new quasar will be an object of study for many years to come. Follow-up observations at millimeter wavelengths with ALMA have already been approved. These observations will shed light on the physical conditions in the quasar host galaxy, such as the temperature and the metal content of the gas that is forming stars. The quasar will also be targeted at various other wavelengths, painting a complete picture: The astronomers have already been given time on the Hubble Space Telescope for near-infrared observations, NASA's Chandra Space Telescope for observations in X-Rays, and infrared observations with NASA's Spitzer Space Telescope.

Furthermore, the quasar will be a prime target for the successor of the Hubble Space Telescope, the James Webb Space Telescope. With this facility, to be launched in 2021, astronomers will be able to disentangle the optical and near-infrared light of the stars in the host galaxy from that of the accreting black hole, and will thus finally be able to detect the stars in that distant galaxy directly.

Finally, the success of locating a quasar at such a large distance will fuel additional searches for these rare objects. Currently, several new facilities are being built that should allow astronomers to discover many more of these quasars in the early Universe – notably ESA's Euclid space telescope, slated for launch in 2021.

Exciting times for reconstructions of some of the earliest phases of cosmic history – and distant quasars will play an important role!

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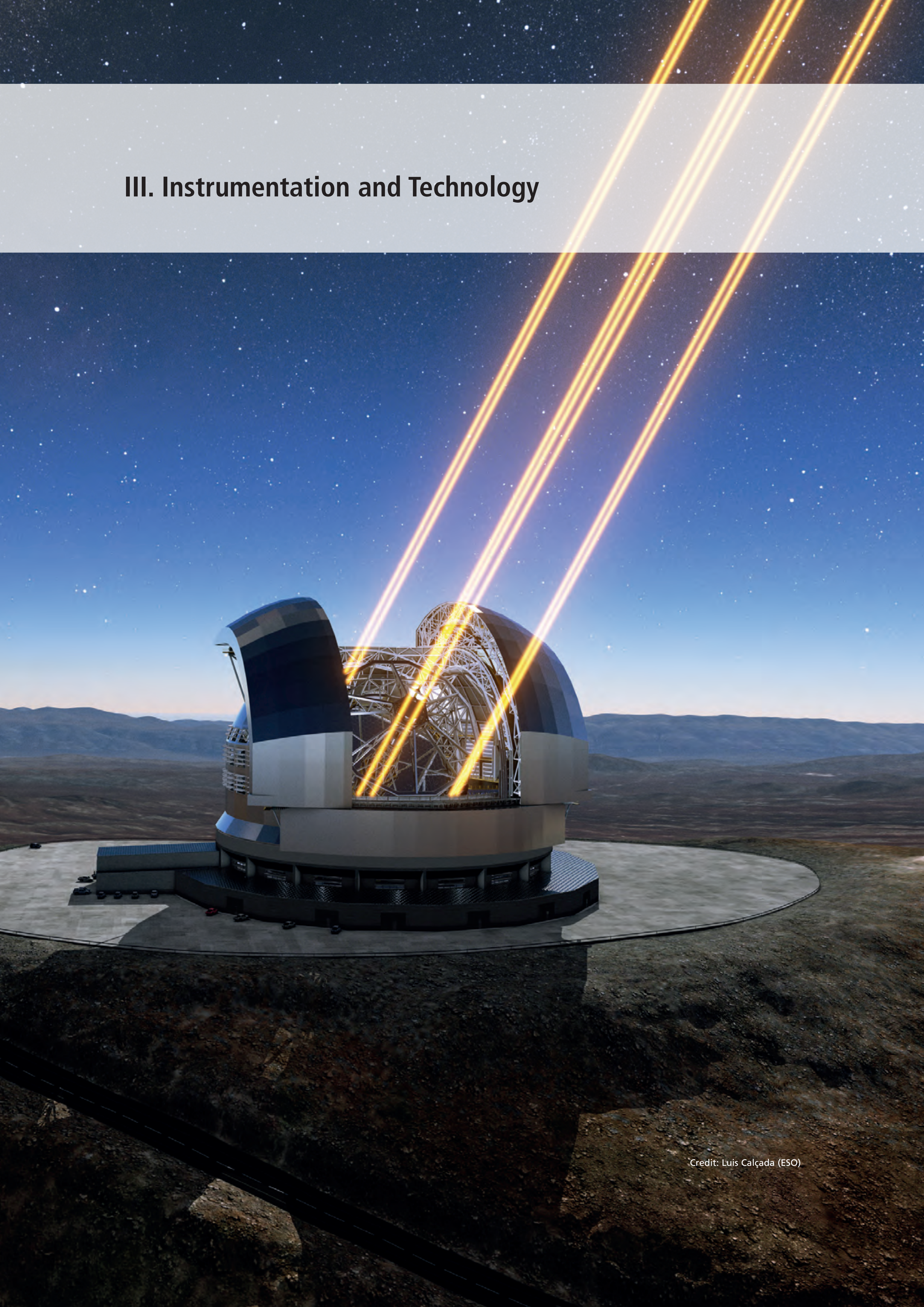
in collaboration with

Eduardo Bañados (Carnegie Institution for Science), Xiaohui Fan (University of Arizona), Chris Carilli (NRAO and Cavendish Laboratory, Cambridge, UK), Feige Wang (Peking University), Joseph Hennawi (University of California, Santa Barbara), Rob Simcoe (MIT) and others

E. Bañados et al. 2017: "An 800 million solar mass black hole in a significantly neutral universe at redshift 7.5" in Nature Vol. 553, pp. 473-476. DOI: 10.1038/nature25180

B. Venemans et al. 2017: "Copious amounts of dust and gas in a $z = 7.5$ quasar host galaxy" in Astrophysical Journal Letters Vol. 851, article id. L8. DOI: 10.3847/2041-8213/aa943a

III. Instrumentation and Technology



Credit: Luis Calçada (ESO)

III.1 Overview

Instrumentation for Ground-based Astronomy

In 2017, MPIA activities in the area of ground-based instrumentation concentrated on spectroscopy, high fidelity imaging, and interferometric instruments for the telescopes VLT/VLTI and VISTA of the European Southern Observatory (ESO) and for the Large Binocular Telescope (LBT), as well as survey instrumentation for Calar Alto. MPIA is also involved in building two of the three first-light instruments for the Extremely Large Telescope (ELT), a next generation telescope with a main mirror of 39 meters in diameter.

Instrumentation for the Large Binocular Telescope (LBT)

The laser guide star system ARGOS for the Large Binocular Telescope (LBT) on Mount Graham in Arizona creates artificial reference stars on the night sky. These guide stars can be used with the two LUCI instruments: two near-infrared cryogenic imaging cameras and multi-object spectrographs built earlier, and upgraded in 2016 by a collaboration involving the MPIA, where these instruments had originally been integrated. For one side of the telescope, ARGOS had first light in 2015 and was commissioned until mid-2015, with major MPIA involvement, while for the other side it had first light in December 2015 and saw several commissioning runs in 2016 and 2017.

LUCI1 and LUCI2 are two near-infrared cryogenic imaging cameras and multi-object spectrographs that have been operational at the LBT in various implementation modes for up to eight years. They provide a $4' \times 4'$ field of view in seeing limited mode – a bit over 1/60 of the apparent area of the full moon in the sky, and extremely wide for an astronomical camera at a large telescope like the LBT. While the instrumentation project per se was finished already in mid-2016, the LUCI instruments continue to be the LBT workhorses for MPIA astronomers.

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

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

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

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

The MATISSE consortium consists of nine institutes led by the Observatoire de la Côte d'Azur. MATISSE combines the light from all four VLT unit telescopes in the mid-infrared for high spatial resolution image reconstruction on angular scales of 10 – 20 milliarcseconds. Scientific applications range from studies of Active Galactic Nuclei (AGN) to the formation of planetary systems and of massive stars, and the study of circumstellar environments. MATISSE was shipped to Paranal in September 2017, and integration started in November 2017.

GRAVITY also combines the light of the four VLT unit telescopes, but in the near-infrared. The GRAVITY consortium is led by the Max Planck Institute for Extraterrestrial Physics in Garching. The partners include MPIA, the observatories in Paris and Grenoble, and the Universities of Cologne and of Lisbon. Assisted by a high-performance adaptive optics system, GRAVITY

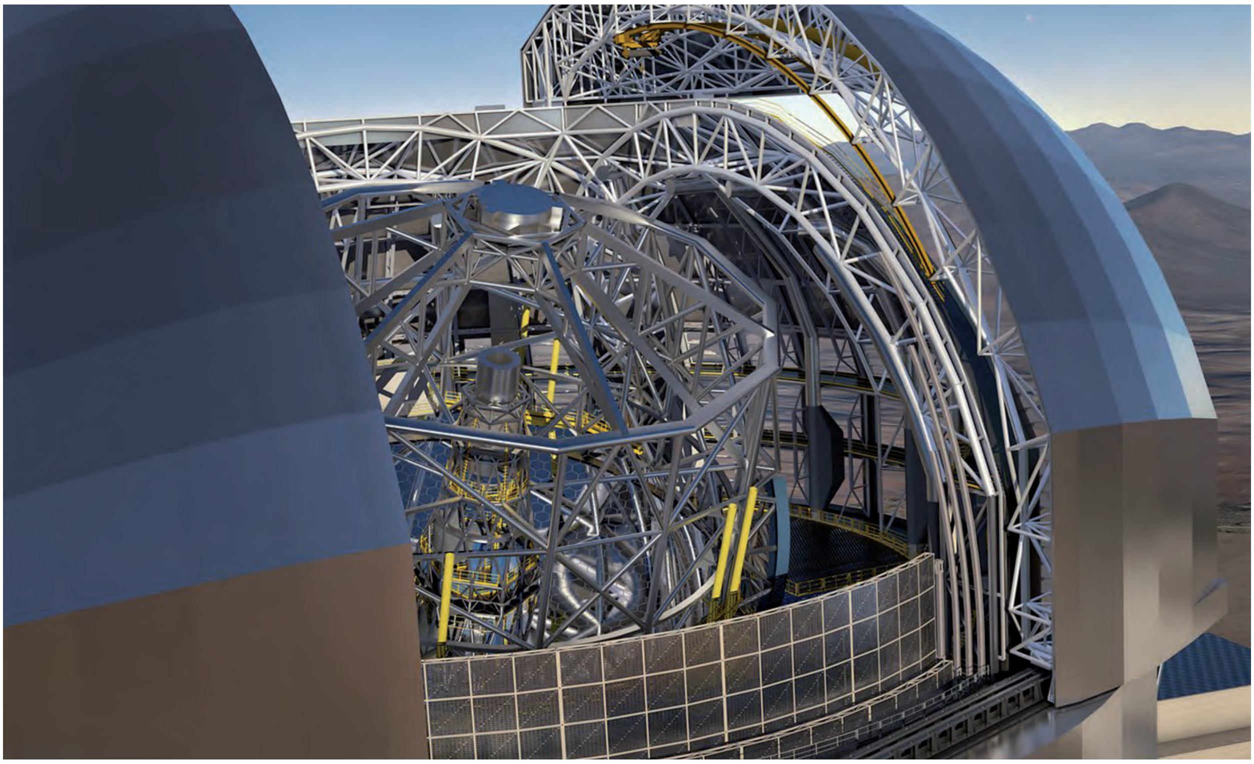


Fig. III.1.1: Computer rendering of ESO's Extremely Large Telescope in its dome on Cerro Armazones in Chile.

provides precision narrow-angle astrometry and phase referenced imaging of faint objects over a field of view of 2″.

While the beam combiner part of the GRAVITY instrument had already been installed on Paranal in 2015 and saw first light in January 2016, other components, such as the metrology system as well as MPIA's main contribution, the four wavefront sensor systems CIAO (short for Coudé Infrared Adaptive Optics), were successfully installed in 2016. Commissioning of the CIAO systems with the GRAVITY beam combiner began in September 2016 and an upgrade was successfully carried out in February 2017. GRAVITY has now been offered to the astronomical community together with the four CIAO systems since the fall of 2017.

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

In particular, GRAVITY observed the S2 object near the Galactic Center in 2017 and continues to do so in 2018 when the object is at its closest approach to the black hole in the Galactic Center. This permits tests of general relativity under extreme conditions of strong gravity.

While the instrumentation project for the exoplanet imager SPHERE at the ESO VLT was completed in late 2015, this instrument is now used extensively by MPIA astronomers and produces a lot of interesting scientific results. The main challenge for SPHERE is to overcome the huge disparity in brightness between extrasolar planets and their host stars. To this end, the instrument uses eXtreme Adaptive Optics (XAO), and coronagraphy (that is, a physical obstruction blocking the star's light in the telescope's optical path). It features three sub-instruments in the focal plane that are capable of differential imaging, that is, of comparing different images of a planet and its host star, with a view towards distinguishing between the image of the planet and various image artefacts. The three sub-instruments employ polarimetry in the visual, dual imagery in the near-infrared, and integral field J-band spectroscopy, respectively.

The project 4MOST, which MPIA joined in 2014, is a multi-object spectrograph for the 4.1 meter VISTA telescope at ESO's Paranal observatory. It is currently in its final design phase, which is expected to end with a two-part review in April 2018 and January 2019. After that, MPIA will deliver its contributions to the partner institutes in 2019. The project is led by the Astrophysical Institute Potsdam. MPIA is responsible for the instrument control electronics. The instrument is supposed to study the origin of the Milky Way and its chemical and kinematic substructure, as well as the evolution of galaxies. To this end it will employ 2,400 fibres over a field of view of 4 square degrees, enabling simultaneous spectrography of up to 2,400 different objects within the field of view.

Survey instrumentation for Calar Alto (CAHA) and other observatories

The Panoramic Near-Infrared Camera (PANIC), operational since April 2015, is a wide-field general purpose instrument for the CAHA 2.2 meter telescope and a joint development of the MPIA and the Instituto de Astrofísica de Andalucía. With four Hawaii2-RG detectors, it provides a field of view of 30′ × 30′ (corresponding to the apparent size of the full moon in the sky), allowing for surveys of extragalactic, galactic, and Solar System objects. A refurbishment project of replacing its detector mosaic by a better quality single Hawaii4-RG detector that will cover the same field of view was prepared in 2017 and will be carried out in 2018 and 2019. Reinstallation on Calar Alto and commissioning are foreseen for early 2020.

CARMENES is a high-resolution near-infrared and optical Échelle Spectrograph at the CAHA 3.5 meter telescope by a consortium of German and Spanish institutions. After successful commissioning of both spectrographs in the second half of 2015, the instrument began its first survey in January 2016. This survey targets 300 M-type main-sequence stars in order to find low-mass exoplanets in their habitable zones.

The search for transiting extrasolar planets by surveying a large number of nearby stars is the goal of the HATSouth project, a collaboration of MPIA with Princeton University, the Australian National University and the Pontificia Universidad Católica de Chile. HATSouth is a network of 24 small, automated telescopes located at Las Campanas in Chile, Siding Springs in Australia, and at the H.E.S.S. site in Namibia. MPIA has been responsible for the site preparation and operations of the Namibian node.

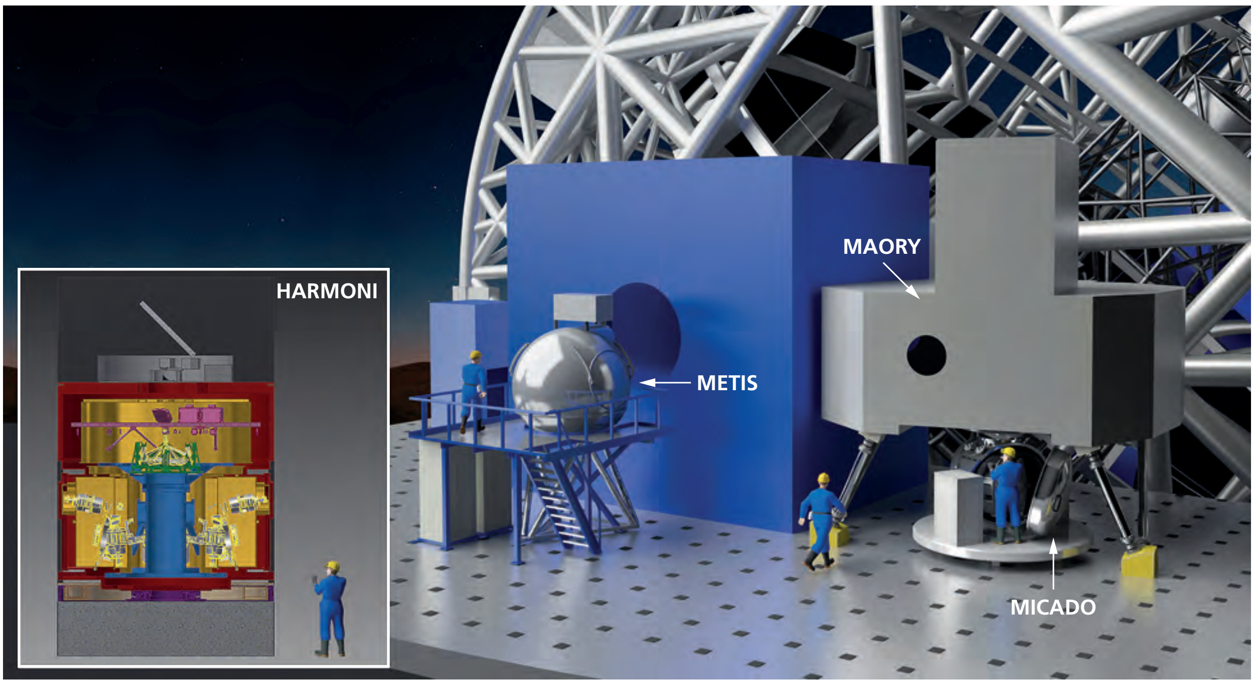
The future Extremely Large Telescope – (E-ELT)

Construction work for the 39 meter Extremely Large Telescope (ELT) will commence in 2018 on the Cerro Armazones mountain in Chile's Atacama Desert, in close proximity to ESO's existing Paranal observatory (Fig. III.1.1).

In late 2014, the ESO council took the decision to move forward with the construction of the telescope and its first-light instruments. MPIA participates in two of the three first-light instrumentation projects: METIS and MICADO (see Fig. III.1.2). Both MICADO and METIS are currently in their preliminary design phases, which are supposed to end in November 2018 and May 2019, respectively. The subsequent final design phases will last until October 2020 for MICADO and until May 2021 for METIS.

METIS is a thermal/mid-infrared imager and spectrograph covering a wavelength range between 3 and 19 microns. Adaptive optics will permit the instrument to perform diffraction-limited observations, making full

Fig. III.1.2: This artist's impression shows the approximate locations of the first-generation instruments on the Nasmyth platform of the ELT. MPIA is currently involved in the instruments MICADO and METIS.



Credit: NOVA/METIS/MAORY/MICADO/HARMONI

use of the telescope's impressive size. The instrument's science case includes exoplanet detection and characterization, the formation and evolution of protoplanetary disks and extrasolar planets, conditions in the early Solar System, studies of the Galactic Center and of the luminous centers of nearby galaxies, high-redshift active galactic nuclei and high-redshift gamma ray bursts.

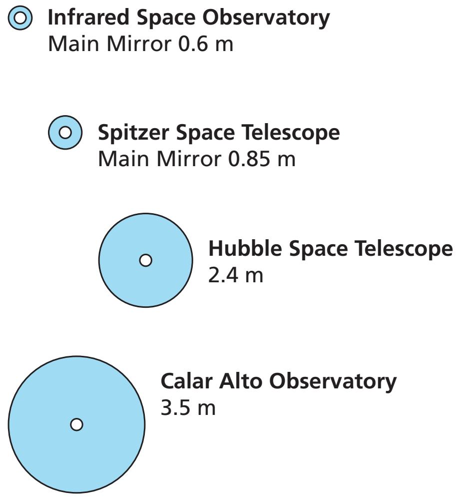
MICADO is a near-infrared imaging camera with multi-conjugated adaptive optics that will provide spatial resolution exceeding that of the James Webb Space Telescope (JWST, the successor to the Hubble Space Telescope) by a factor between 6 and 7. MICADO will be sufficiently sensitive to observe stars down to a brightness of 29 magnitudes – in visible light, this would include stars more than a billion times fainter than are visible with the naked eye – in the near-infrared bandpasses from I to K.

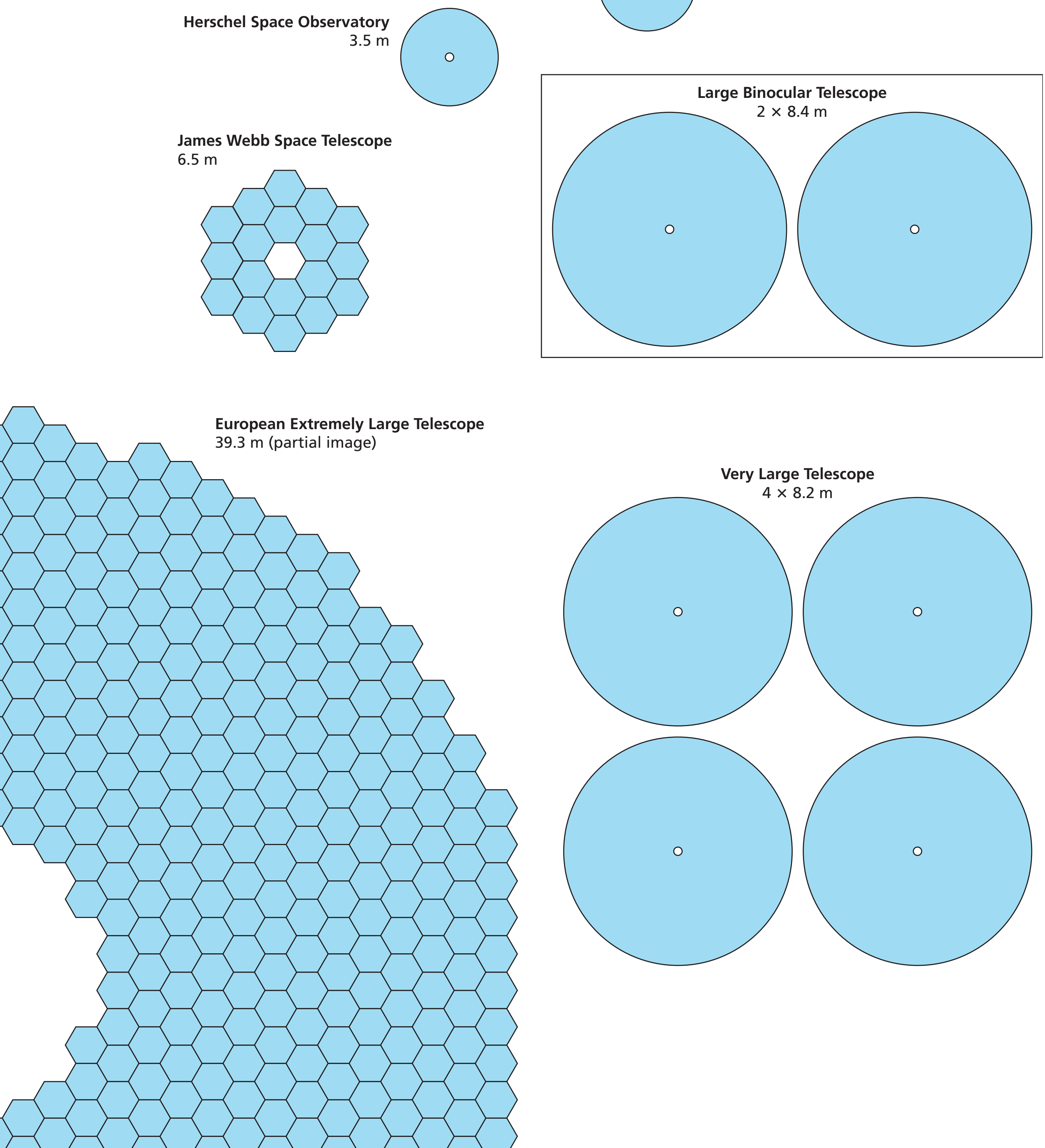
Scientific goals for MICADO include fully resolving stellar chemical and kinematical properties in the centers of galaxies, star clusters, and stellar populations in the Local Group (the group of galaxies to which our own galaxy, the Milky Way, belongs), detailed morphological galaxy studies at high 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

Telescope Mirror Sizes

Shown here are shape, structure and size of the main mirrors of selected telescopes that are used by MPIA scientists. For a number of these telescopes, MPIA has contributed or is contributing to instrumentation.





III.2 Overview

Instrumentation for Space-based Astronomy

James Webb Space Telescope (JWST)

The James Webb Space Telescope (JWST), a space telescope for wavelengths from visible light to the mid-infrared, will be launched on an Ariane 5 rocket from French Guiana in 2021. With its cold 6.5 meter primary mirror and four science instruments, JWST will be the premier infrared observatory in space for a decade to come. It will study every phase in the history of our Universe, ranging from the first luminous glows after the Big Bang, to the formation of solar systems capable of supporting life on planets like Earth, to the evolution of our own Solar System.

MPIA is the leading institute in Germany for the development of instrumentation for the JWST. As a member of a European consortium, MPIA is responsible for developing the cryogenic wheel mechanisms required for precise and reliable positioning of the optical components in JWST's mid-infrared instrument MIRI, and is also leading the electrical system engineering of this instrument. MIRI consists of a high-resolution imager and a medium resolution spectrometer and will work in the wavelength range from 5 to 28 micrometers.

MPIA has also delivered vital components such as cryogenic motors and high-precision position sensors for the near-infrared multi-object spectrograph NIRSPEC, the second of two JWST science instruments that have been developed mainly in Europe. Both departments of the institute will benefit from the outstanding observational capabilities of JWST, and the institute is deeply involved in the definition and preparation of observing programs.

Fig. III.2.1: The James Webb Space Telescope after it emerged from Chamber A at NASA's Johnson Space Center in Houston on Dec. 1, 2017.

Credit: NASA


Credit: NISP Team/LAM

Fig. III.2.2: Flight model of Euclid NISP's mechanical structure, freshly arrived at the integration facility cleanroom in Marseille. This structure is made of extremely light yet strong Silicon Carbide ceramics and is the mounting point for all optics and detector components.

JWST underwent critical cryogenic testing inside Chamber A during the year 2017, a massive thermal vacuum chamber at NASA's Johnson Space Center in Houston, Texas (Figure III.2.1). The chamber is big enough to contain the deployed JWST telescope in order to verify its optical and thermal performance at the same cryogenic operating temperature of 50 Kelvin (–223° C) and high-vacuum akin to its orbit at Earth's second Lagrange point (L2). The same 16.8 meter diameter × 27.4 meter high, thermal-vacuum test facility was previously used for testing the Apollo spacecraft of the moon program.

JWST arrived at Johnson in May 2017, inside a massive, specially designed shipping container called the Space Telescope Transporter for Air, Road and Sea (STTARS) which just fits a huge C-5 Galaxy transport aircraft. Upon its arrival, engineers moved STTARS into the Chamber A cleanroom and carefully unpacked the telescope's combined optical element and science instruments from it.

In June 2017, engineers deployed JWST's primary mirror wings and secondary mirror tripod, which is the same configuration the optical element will have when it deploys in space. The engineers then loaded JWST on a platform designed to hold the telescope inside Chamber A, and slowly and deliberately moved JWST inside the chamber along a set of rails. Even with the chamber's 12.2 meter diameter entrance, the fully extended secondary mirror tripod made it a tight fit for JWST.

On July 10, Chamber A's colossal door closed, signaling the beginning of cryogenic testing. During approximately 100 days in the chamber, scientists and engineers at Johnson put JWST through a series of tests designed to ensure the telescope functioned as expected in an extremely cold, airless environment akin to that of space.

Before cooling the chamber, engineers removed the air from it, which took about a week. On July 20, engineers began to bring the chamber, the telescope, and the telescope's science instruments down to cryogenic temperatures — a process that took about 30 days. JWST remained at "cryo-stable" temperatures for about another 30 days, and on Sept. 27, the engineers began to warm the chamber back to ambient conditions (near room temperature), before pumping the air back into it and unsealing the door. JWST emerged from Chamber A on Dec. 1, riding out on the same rail system that carried it in.

The MPIA JWST team significantly contributed to the preparation, execution and analysis of these tests on site. The MPIA team is also deeply involved in developing the future data processing pipeline for the MIRI instrument.

In early 2017, JWST underwent vibration and acoustic testing at NASA's Goddard Space Flight Center in Greenbelt, Maryland, which showed the telescope will survive the rigors of launch. Among the tests performed on JWST inside Chamber A was an important alignment check of the telescope's 18 primary mirror segments, to make sure all of the gold-plated, hexagonal segments acted like a single, monolithic mirror in a space-like environment. This test also showed JWST's science instruments were properly aligned with its mirrors and could detect simulated "starlight" within the chamber.

At the end of 2017 JWST's combined science instruments and optics were prepared to be shipped to the facilities of the prime contractor Northrop Grumman Aerospace Systems in Redondo Beach, California, where they will be integrated with the spacecraft element, which is the combined sunshield and spacecraft bus. Together, the pieces form the complete James Webb Space Telescope observatory.

Euclid

ESA's Euclid mission is set to launch in the early 2020s as a probe into the nature of dark matter and dark energy. Euclid will utilize high-fidelity imaging and spectroscopy in the visual and near-infrared wavelength ranges to measure distance, spatial distribution and shape of a billion galaxies over nearly half the sky. Its goal is to measure the evolution of cosmic expansion and the distribution of dark matter across cosmic time from 10 billion years in the past (redshift $z = 2$) to today.

MPIA's hardware contribution to NISP, the France-led near-infrared imaging and spectroscopy instrument onboard Euclid, has turned onto its home stretch in 2017. Flight hardware went into full manufacturing, with a completion and delivery planned for mid-2018. The same is true for NISP's other components, with the mechanical structure being the first to be assembled at LAM Marseille (Figure III.2.2).

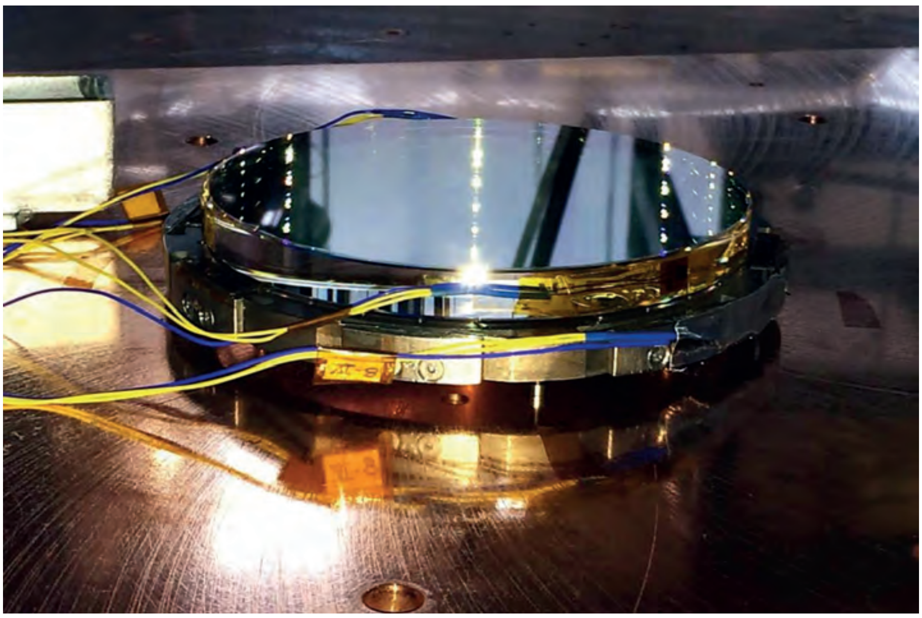
Overall two hardware components are provided by MPIA: near-infrared filters, to provide the instrument with three distinct photometric bandpasses between 950 nm and 2000 nm and a calibration light source featuring LED illumination at five wavelengths in the same range, both funded by the German national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

The filters are close to being completed. First high-transmittance Zerodur 3001 glass blanks of 130 mm diameter have been ground and polished into shape in France. Then the bandpass-defining interference coating process started at Optics Balzers Jena, to be completed early 2018. Acceptance tests and bandpass characterization follow. A first qualification model has been completed to be used in the Spain-led filter wheel assembly engineering qualification model. The final two sets of each three flight and spare filters will be delivered until mid 2018, completing MPIA's filter manufacturing involvement, with only some residual characterization and testing following later in the year.

The second hardware contribution is a near-infrared calibration lamp that has been designed under MPIA responsibility. Five different LED types were constructed and qualified for this purpose, allowing the lamp to illuminate the NISP detector array with a very stable amount of light at five different wavelengths, and thereby calibrate its sensitivity. The flight model and spare of this light source came close to completion in 2017, to be delivered in 2018 to Marseilles.

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

Fig. III.2.3: Euclid NISP Y-band qualification model infrared filter as seen in a test setup. Attached are temperature sensors to trace how properties change between different conditions.



Credit: MPIA/Optics Balzers Jena/AMOS

Credit: MPIA

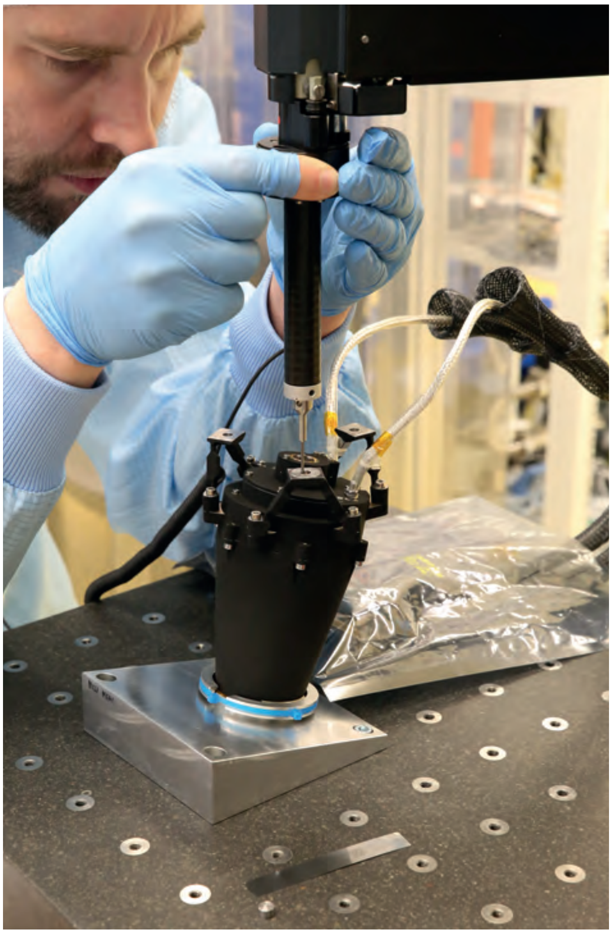


Fig. III.2.4: Final measurement of geometry and mounting interfaces for the NISP calibration lamp. Here the lamp is sitting upside down in the MPIA cleanroom for a measurement to confirm that the position of its six connecting legs are exactly as planned.

Overall, Euclid at MPIA is well on track towards a completion of the NISP instrument and start of testing towards the end 2018, and integration into the payload module at ESA in 2019. MPIA's involvement in Euclid will not stop there. It will shift more towards contributions to the computing ground segment, after launch to operating NISP and assessing its performance, and beyond that to science exploitation of the vast and unprecedented dataset.

This will include highly interesting analyses outside the mission's nominal main science goals: With a substantial high spatial-resolution visible imaging dataset (0.1 arcseconds) and deep infrared data (signal-to-noise ratio S/N = 5 for point sources at magnitude 24) for over a third of the sky, the possible science applications are vast, ranging from observational studies of galaxy evolution and maybe even to the discovery and characterization of exoplanets.

Oliver Krause for the IR Space Group
and
Knud Jahnke for the Euclid Group

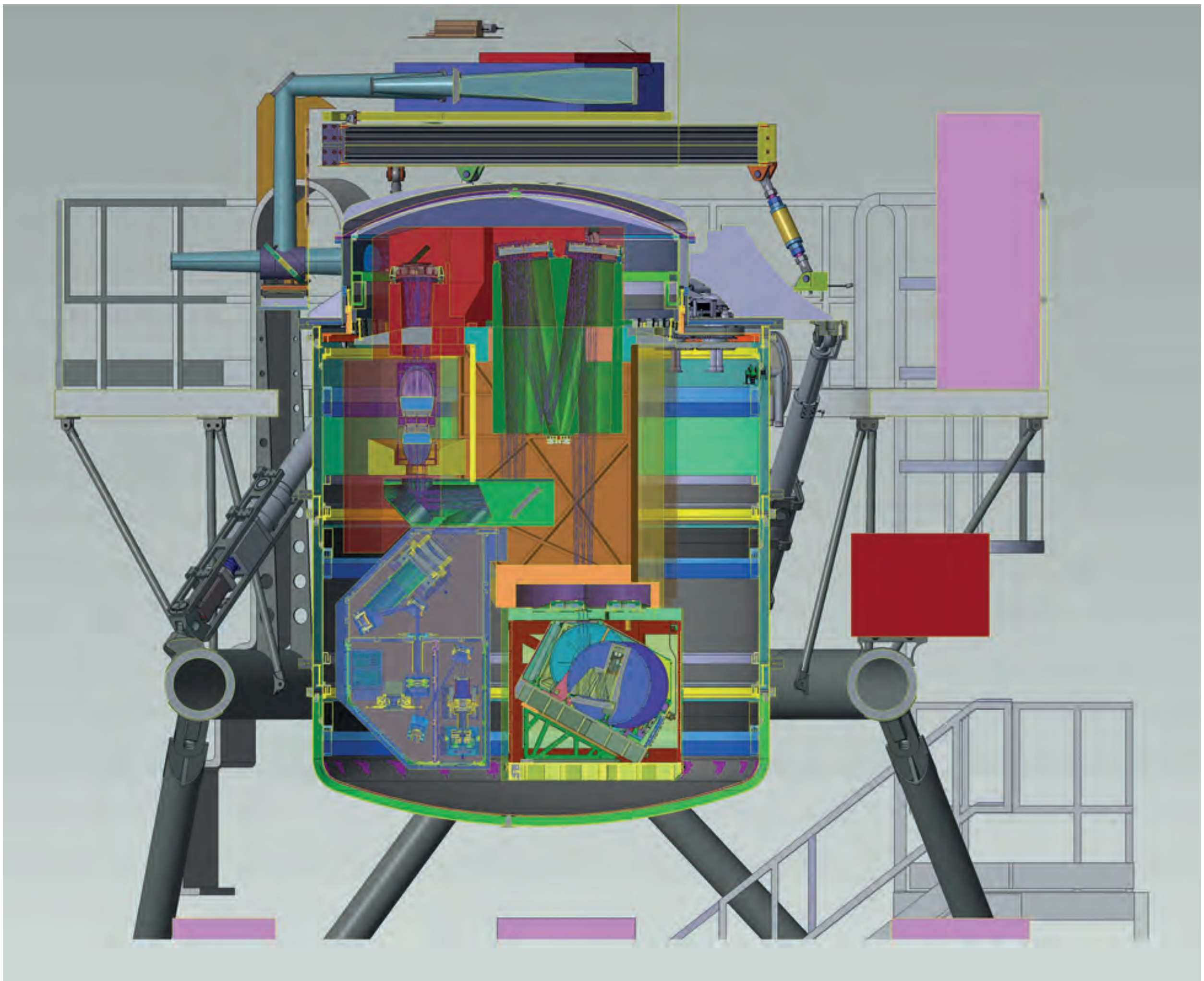
METIS – a camera and spectrograph for the Extremely Large Telescope

The camera and spectrograph combination for the Mid-Infrared ELT Imager and Spectrograph (METIS) is one of the first three instruments planned for the European giant telescope ELT (Extremely Large Telescope).

METIS will offer several modes for scientific operation. A camera mode at infrared wavelengths between 3 and 19 micrometers will be provided by two cameras, one for operation between 3 micrometers and 5 micrometers ("LM"), and one for images between 5 micrometers and 19 micrometers ("NQ"). In addition to pure imaging, this mode will also allow for low-resolution ($R \sim 100$) slit spectroscopy, and for the application of a coronagraph for images with contrasts of up to $1{:}10^5$ at apparent separations of the star and a planet of down to $5 \times \lambda/D$, with D the telescope diameter and λ the wavelength.

The second mode allows for high resolution (R~100,000) integral field spectroscopy between 3 micrometers and 5 micrometers, including the option of extended wavelength coverage (making for a spectrum 300 nm instead of 50 nm wide). This mode, too, can be combined with coronagraphy.

Fig. III.3.1: Cross section of the METIS cryostat. Bottom left is the wavefront sensor, in the center one of the two cameras.



Credit: MPIA (Rohloff f. Design, Cárdenas f. Optik)

METIS is supported by an (extreme) adaptive optics (AO) system that allows for diffraction-limited operation at the ELT with very high image quality. The resolution of the system at the smallest wavelength of 3.5 micrometers is about 23 milliarcseconds.

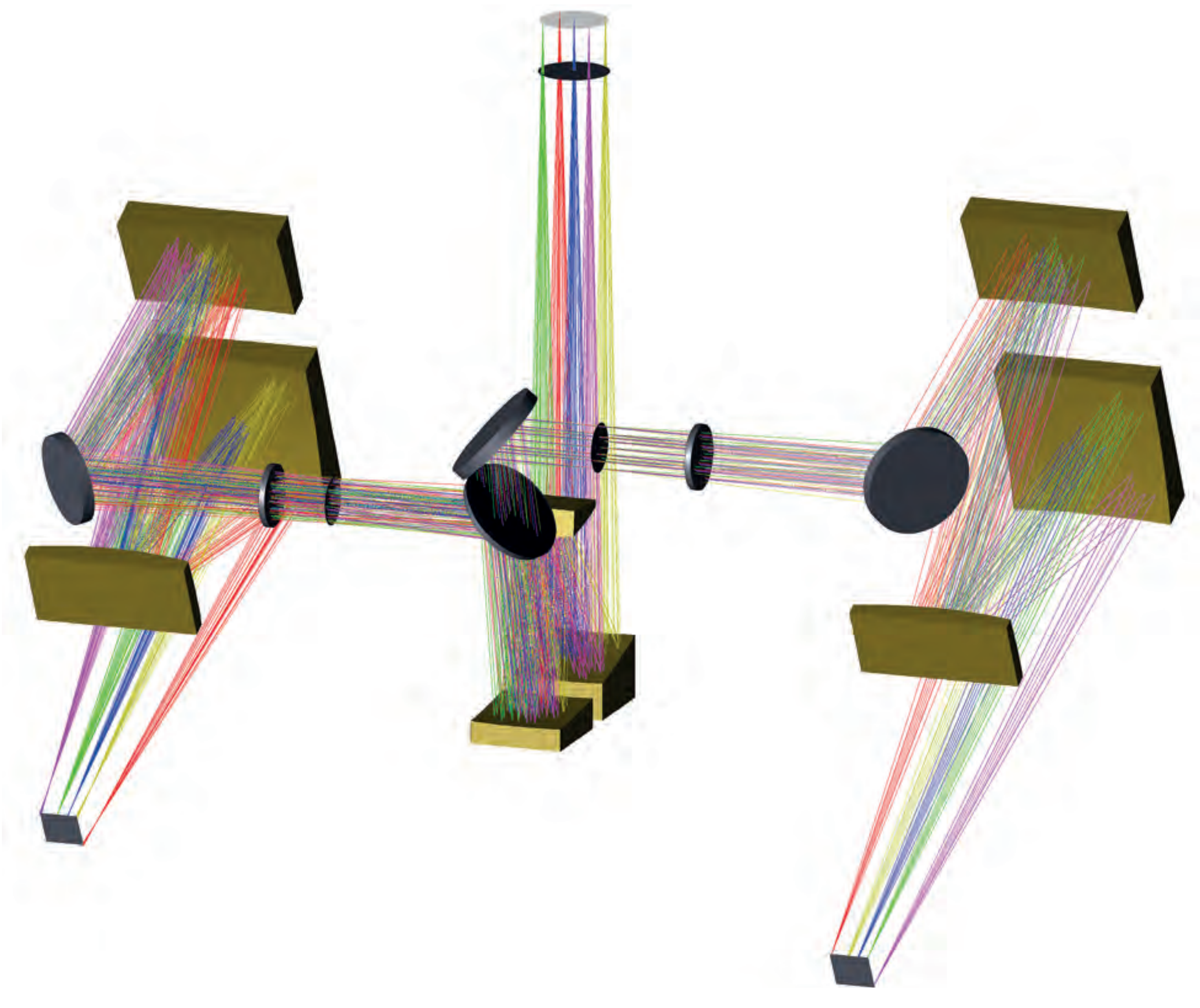
Scientifically, METIS mainly targets compact objects such as extrasolar planets and circumstellar disks. The field of view is correspondingly small and is about 10″ × 10″ for both camera systems and 1″ × 0.5″ for integral field spectroscopy.

METIS is built by a consortium led by NOVA, an association of Dutch universities. The MPIA is the second largest partner in the consortium and is in charge of providing the two camera systems and adaptive optics.

Due to the planned operation in the thermal infrared, METIS and all its components including the wavefront sensor for the adaptive optics will be located in a closed cooling vessel (dewar). Most of the components are kept at a temperature of 70 K. An exception is the NQ camera, which is held at 25 K, while some detectors are cooled down to 8 K. Figure III.3.1 shows a sectional view based on the current design drawings. The lower part shows the key contributions of the MPIA: the wavefront sensor and the camera units.

The design of both the pre-optics and the two cameras is based entirely on reflective elements and consists of a collimator, a dichroic mirror and the two cameras (Figure III.3.2). The LM camera has an image scale of 5.47 milliarcseconds per pixel on its Hawaii-2RG detector, while the NQ camera maps 11.32 milliarcseconds per pixel on its Aquarius detector. Both the collimator in the pre-optics and the two cameras are realized by 3-mirror anastigmatic systems (TSAs). All mirrors are made of aluminum and are gold-plated. In addition, the first and third mirrors of all three TSAs are produced as free-form optics on a common diamond substrate, shaped using a specialized milling process. This approach means that the deviations in both shape and

Fig. III.3.2: Optical design of the pre-optics and the two cameras with their anastigmatic mirror systems. Clearly visible are the two mirrors 1 and 3 of all three systems, which lie in a common plane. They are manufactured as free-form optics on common substrates.



Credit: MPIA (Rohloff f. Design, Cárdenas f. Optik) relative position are less than one micrometer. This reduces the complexity of the system alignment, as there are fewer degrees of freedom and the necessary accuracy can be achieved more easily.

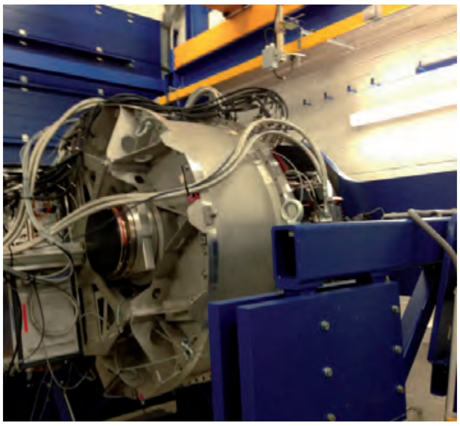
The wavefront sensor is based on the pyramid principle. The 4-sided, transparent pyramid is placed in the system's focus and divides the beam into 4 parts, each of which individually generates a pupil image on the SAPHIRA detector. The magnification, which determines the sampling, corresponds to 0.5 m/pixel. Intensity ratios between the individual pupils then allow the input wavefront to be reconstructed. The signal is read out with a frequency of 1 kHz, processed and the information passed on to the ELT's M4 and M5 correction mirrors.

Markus Feldt (METIS Co-I)

III.4 Instrumentation at MPIA

Overview of current projects

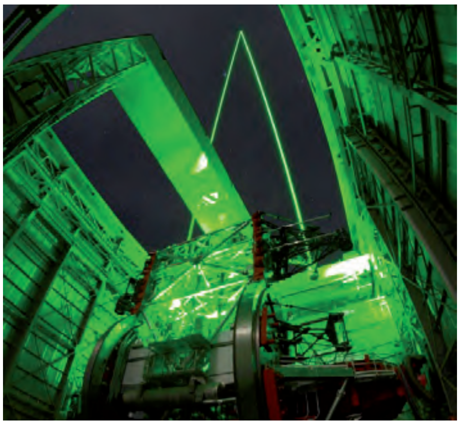
Astronomical instruments have different strengths and specializations. Here, we list **ongoing MPIA instrumentation projects for the year 2017.** Almost all of the instruments are cameras for producing astronomical images, spectrographs for analyzing the component colors of light, or combinations thereof. The only exception is Argos, which enables other instruments to take sharp images by projecting an artificial laser star into the sky.



LUCI 1 + 2

LBT NIR spectroscopic Utility with Camera and Integral-Field Unit

Telescope	Large Binocular Telescope, Mt. Graham
Wavelength range	Near-infrared, 0.85 – 2.5 µm
Targets	Galaxy clusters and star clusters
Resolution	30 – 90 mas (wavelength-dependent with AO)
Special features	Can examine multiple objects at once
MPIA contribution	Electronics, software, detectors, cryogenics, integration facility
Status	Operational. MPIA part of project ended



ARGOS

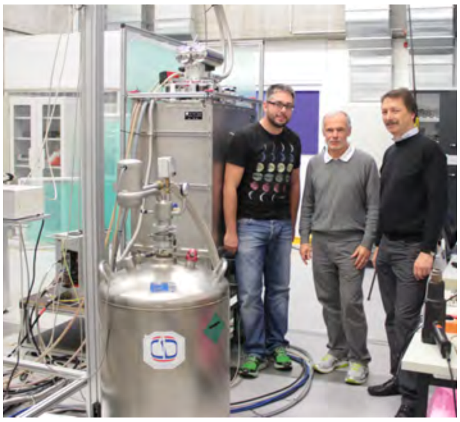
Advanced Rayleigh guided Ground layer adaptive Optics System

Telescope	Large Binocular Telescope, Mt. Graham
Wavelength range	-
Targets	-
Resolution	-
Special features	Can examine multiple objects at once
MPIA contribution	Testing, control software/motor control, calibration, alignment
Status	Binocular operation mode using both LUCIs achieved

LINC-NIRVANA

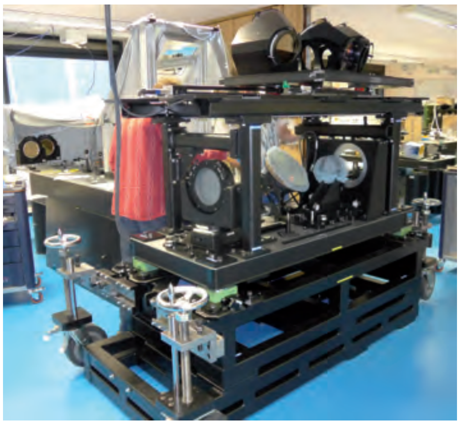
LBT INterferometric Camera –
Near-InfraRed Visual Adaptive interferometer for Astronomy

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



MATISSE
Multi AperTure mid-infrared SpectroScopic Experiment

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



GRAVITY

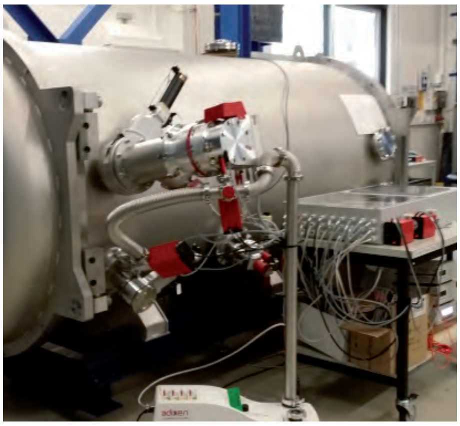
Telescope	Very Large Telescope, Paranal, Chile
Wavelength range	Near-infrared, 2.2 μm
Targets	Milky Way black hole, planets, brown dwarfs, disks/jets, AGN
Resolution	4 mas for imaging
Special features	High-precision narrow-angle astrometry down to 10 mas
MPIA contribution	Four wavefront sensors for the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

4MOST
4 meter Multi-Object Spectroscopic Telescope

Telescope	VISTA Telescope, Paranal, Chile
Wavelength range	420 – 900 nm
Targets	Milky Way and galaxies, structure of the cosmos
Resolution	Spectral resolving power of 5,000 – 20,000 (spatial resolution n/a)
Special features	2,400 fibres over a field-of-view of 4 square degrees
MPIA contribution	Instrument control electronics
Status	Final design phase

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

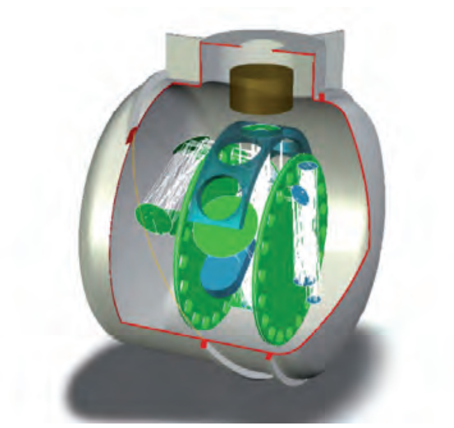
Astronomical objects are extremely distant, making it difficult to discern any details. The **resolution** is a measure of the level of detail that can be achieved using a particular instrument. Resolution is given as an angle on the sky: a resolution of 0.1 arcseconds means that, say, an astronomical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



CARMENES

Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs

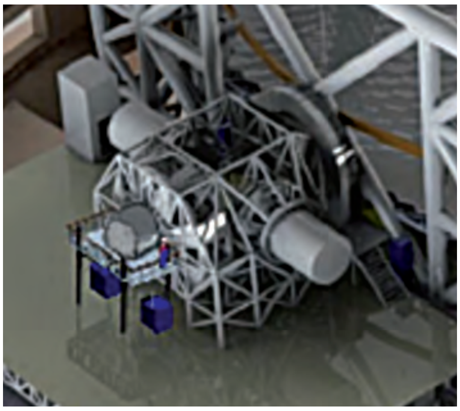
Telescope	3.5 meter Telescope, Calar Alto
Wavelength range	Near-infrared and visible light, 0.5 – 1.7 μm
Targets	Planets around 300 M dwarf stars including Earth-like planets
Resolution	High spectral resolving power of 82,000 (spatial resolution n/a)
Special features	Two high-precision spectrographs for radial velocity measurements
MPIA contribution	NIR detector/cryostat, electronics, software, integration facility
Status	Operational, survey underway, instrumentation project ended



MICADO

Multi-AO Imaging Camera for Deep Observations

Telescope	European 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	Cold filter wheel, astrometric calibration
Status	Preliminary design phase

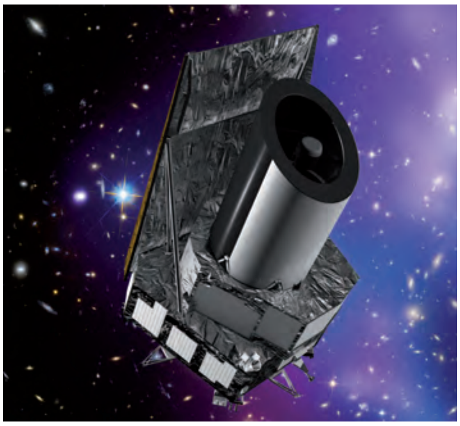


METIS **Mid-infrared E-ELT Imager and Spectrograph**

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

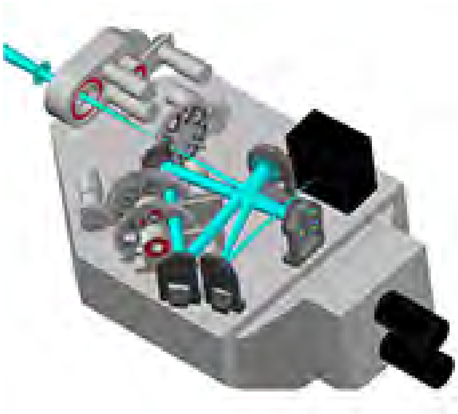
Specific instruments have **characteristic** special features or properties. A particularly wide field of view, for instance, allowing for survey images of larger regions of the sky. Adaptive optics counteracts atmospheric disturbances. Other examples are the ability to determine the orientation in which 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.



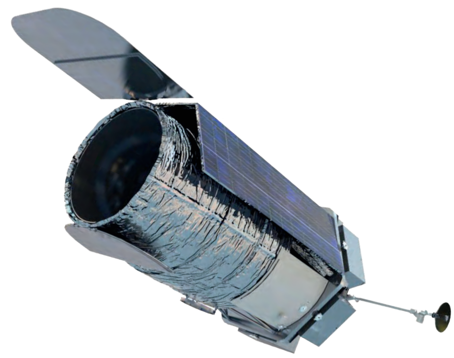
EUCLID

Telescope	Euclid denotes the whole space telescope
Wavelength range	Visible light, 0.5 – 0.9 µm, and infrared light, 0.965 – 2.0 µm
Targets	Tracing cosmic large-scale structure and cosmic acceleration
Resolution	86 – 344 mas depending on wavelength
Special features	Galaxy morphology, IR photometric redshifts and spectroscopy
MPIA contribution	Part of infrared detector calibration unit, large
Status	Flight models completed in industry; MPIA part of instrumentation project finished



SHARK-NIR

Telescope	Large Binocular Telescope, Mt. Graham
Wavelength range	Near-infrared, 0.96 – 1.7 µm
Targets	Direct detection of extrasolar planets
Resolution	Imaging: 30 – 50 mas, spectroscopy: R ~100 & 800
Special features	Various choronagraphic techniques
MPIA contribution	Motor control unit
Status	MPIA contributions delivered



WFIRST

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

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

III.5 Highlight

Technical Departments

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

MPIA's technical departments comprise the engineering design department, the precision mechanics workshop, the electronics, software, and instrumentation departments. These departments with their workshops and design offices participate in the development and

Fig. III.5.1: Tangible results of the project work undertaken during the vocational training: scale models of different TV towers.

Credit: MPIA

construction of cutting-edge astronomical instruments which are then deployed at sites such as Calar Alto Observatory, the telescopes of the European Southern Observatory (ESO), the Large Binocular Telescope, or aboard ESA or NASA space telescopes.

Vocational training of precision mechanics

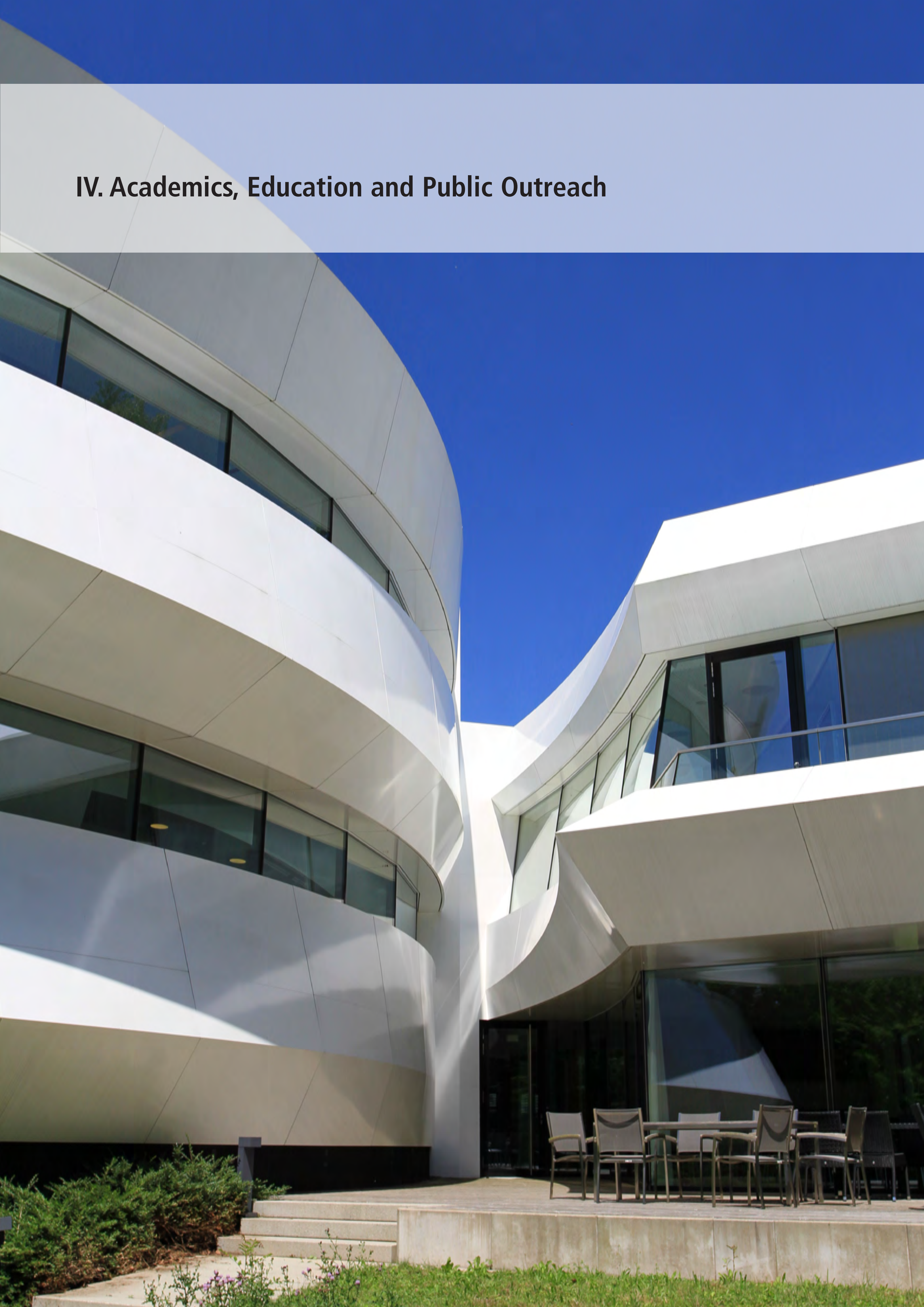
The precision mechanics workshop is one of the mainstays of MPIA's technical departments, and is competitive world-wide when it comes to mannfacturing mechanical systems for use in a space environment. Recently, the workshop introduced a new concept for the vocational training on CNC machines. In the framework of a project, the apprentices produced model workpieces (e.g. of TV towers, see figure) using CNC devices such as lathes and milling machines. They were responsible for planning their projects, as well. A major difficulty lies in the fact that all models must be created on a given scale and with the highest possible accuracy when it comes to detail. This fosters the training and application of technical skills and know-how.

For the basic vocational training, the workshop developed a new strategy, as well. The program now takes into account an apprentice's learning style (visual, auditive, communicative or motor), and customizes the training accordingly. In addition, a yearly workshop offers the opportunity both for advanced technical training over a broad range of subject areas, and to foster social and personal skills. Workshops include self-study materials for sustained learning. Every apprentice also gives a talk on a specialist subject. Those subjects include examples from very different fields of work, in order to cover a broad range of technical expertise. Speakers not only prepare the talks themselves; frequently, they also create handouts summarizing the key points of their talks. This helps the workshop participants deepen their technical knowledge.

The particular task of giving a talk significantly boosts personal development of the apprentices, and helps them to build (and display!) confidence in their knowledge. The talks regularly lead to intensive discussions among the apprentices. Typically, the apprentices resolve questions, and arrive at suitable answers, without their instructor's direct assistance.

Stefan Meister, Tobias Stadler,
Armin Böhm and Martin Kürster

IV. Academics, Education and Public Outreach



IV.1 Overview

Academics

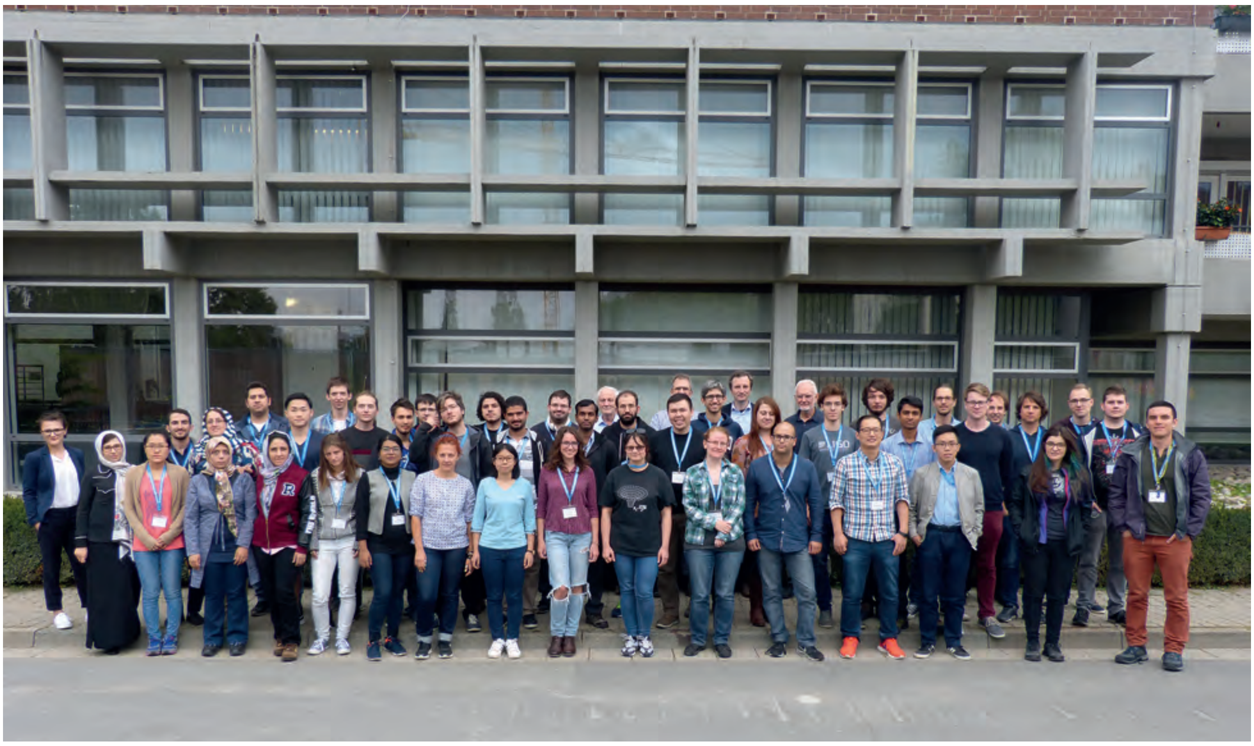
As a research institute, MPIA takes its responsibility for fostering future generations of scientists seriously. Our involvement begins at the undergraduate level. Both the directors and the research group leaders are involved in teaching at Heidelberg University. For instance, this year MPIA scientists were involved in teaching the cosmology block course (Hans-Walter Rix) and the Galactic and Extragalactic Astronomy Block Course (Nadine Neumayer), as well as a lecture course on Star Formation (Thomas Henning, Henrik Beuther) and seminars on topics as diverse as galactic archaeology (Maria Bergemann, Karin Lind) and the physics of interstellar travel (Coryn Bailer-Jones).

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

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

After the successful evaluation of the IMPRS in 2015, the year 2017 started off the school's third 6-year funding period. There was once more a strong pool of applicants (220 applied in 2016), and we were able to offer projects to 20 new PhD students in Heidelberg. Among these, 10 were female, and 11 were of non-German citizenship.

The overall number of IMPRS-HD students in Heidelberg has remained stable at about 90 students – with unavoidably strong seasonal variations, as new students start their work in autumn, while thesis defenses commonly happen in spring.



Credit: C. Fendt (MPIA)

Fig. IV.1.1: Participants of the 12th IMPRS-HD summer school, "Compact Objects & Gravitational Waves".

Country of origin	Initial applicants	Shortlisted applicants
Chile	13	7
China	10	3
India	50	14
Germany	30	20
Iran	16	2
Italy	20	8
UK	7	6
US	9	4

Table IV.1.1: Selected countries of origin for 2017 IMPRS applicants.

With the 13th student generation starting in 2017, the cumulative number of PhD students accepted into the IMPRS-HD has reached 339. The IMPRS-HD fellowships – funding the position directly with IMPRS money – given to the best applicants of 2017 were awarded to Neige Frankel and Melanie Kaasinen.

Among the 229 applicants in 2017 (for PhD positions that start in 2018), 74 were female. This corresponds to 32%, and the same percentage was carried over to the shortlist. Some countries of origin both for the initial and for the short-listed applicants can be seen in Table IV.1.1. Application numbers from India have been up for the past few years, while the formerly high number of Chinese applications has been decreasing lately. Twenty IMPRS students completed their PhD in 2017. The MPIA students among them are listed in Table IV.1.2.

The annual IMPRS-HD international summer school is another success story. The 2017 IMPRS-HD summer school – the 12th of its kind – was dedicated to “Compact Objects & Gravitational Waves”. The scientific program was organized by Andreas Bauswein and Friedrich Roepcke (HITS) as well as Rainer Spurzem (ARI). Invited lecturers included Thomas Baumgarte (Bowdoin College, Brunswick), Tobias Fischer (University of Wroclaw), Paulo Freire (MPIfR, Bonn), Ewald Müller (MPA, Garching), and Nikolaos Stergioulas (Aristotle University, Thessaloniki). As always, the school was announced internationally. In the end, a total of 48 applicants were accepted for participation, including 40 of non-German citizenship.

Christian Fendt

Table IV.1.2: List of PhD projects completed at MPIA in 2017.

Name	Defense Date	Title	Supervisor
Richard Teague (UK)	20 January	Tracing the Earliest Stages of Planet Formation through Modelling and Sub-mm Observations	Henning
Jorge Abreu Vicente (Spain)	25 January	Molecular Cloud Structure at Galactic Scales	Henning
Nina Hernitschek (Germany)	26 January	Astrophysical Modeling of Time-Domain Surveys	Rix
Jakob Herpich (Germany)	08 May	On the Physical Origin of Radial Surface Density Profiles in Disk Galaxies	Rix
Qian Qian (China)	10 May	Accretion and ejection in resistive GR-MHD	Fendt
Richard Hanson (Germany / UK)	19 May	Mapping 3D Extinction and Structures in the Milky Way	Bailer-Jones
Paul Mollière (Germany)	12 July	Modeling of Exoplanet Atmospheres	Henning
Kirsten Schnuelle (Germany)	27 July	Studying the Radiative Response of Circumnuclear Dust of AGNs	Pott
Daniele Sorini (Italy)	17 October	Constraining the physics of the intergalactic and circumgalactic media with Lyman-alpha absorption	Hennawi
Kaylan Kumar Radhakrishnan Santhakumari (India)	22 November	Maximising the Science Returns of the LINC-NIRVANA Multi-Conjugated Adaptive Optics System	Herbst
Wilma Trick (Germany)	27 November	Action-based Dynamical Modeling for the Milky Way Disks	Rix

IV.2 Academics, Education and Public Outreach

Public Outreach

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

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

For members of the general public, guided tours of the Königstuhl Campus offer a chance to experience a research environment at first hand. The tour guides are the MPIA Outreach Fellows: PhD students at the 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 neighbors, created by MPIA's technical departments. The guided tours are offered in cooperation with the neigbouring Landessternwarte.

MPIA also has offers aimed directly at high school students. One is the High School Internship program (organized by Klaus Meisenheimer), aimed at pupils in 10th and 11th grade. In coorperation with the Landessternwarte

Fig. IV.2.1: Participants of the 2017 Girls' Day at Haus der Astronomie.

Credit: HdA

Credit: M. Pössel (MPIA)

Fig. IV.2.2: Hubert Klahr of the PSF department in front of the cameras of a Spanish documentary film crew on May 12, 2017.

warte and Astronomisches Rechen-Institut (both part of Heidelberg University's Center for Astronomy, ZAH), we have been offering this kind of internship program since 2002. This year's internship program, on October 9–13, introduced 10 pupils to basic concepts as well as to practical methods of astronomy.

In addition, in cooperation with HdA, the MPIA is a regular participant in the nation-wide Girls' Day: a one-day program aimed at female pupils aged between the ages of 13 and 18 (organization: M. Pössel, R. Hubele, S. Brümmer). The purpose of Girls' Day is to provide female pupils with the opportunity of experiencing professions in which women are underrepresented. For this year's Girls' Day on April 27, 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 galaxies and star clusters.

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

IV.3 Academics, Education and Public Outreach

Haus der Astronomie
Center for Astronomy Education and Outreach

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

Haus der Astronomie is an unusual institution at the interface between science and the public. Its custom-built, galaxy-shaped building hosts an active team of astronomers and astronomy educators dedicated to developing and producing materials and resources for the public or for use in schools. In 2017, the HdA building received more than 12,000 visitors: members of the general public coming for guided tours or popular talks, student groups from kindergarten to university level, educators and teachers participating in workshops or lectures, and scientists and engineers attending meetings or conferences.

Astronomy for the 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, we provide support for the German-language outreach activities of ESO, the European Southern Observatory.

On-site events for the public included our monthly series of talks "Fascinating Astronomy", with a total of 14 events and "Sunday a.m. Astronomy" with five events on the topic of "The Milky Way: Our Fascinating Home Galaxy" in cooperation with the SFB 881 "The Milky Way System" (R. Hubele), and two family events at Christmas time (N. Fischer, E. Kolar). Our "Science meets fiction" format of combining short scientific talks with the presentation of a science fiction movie continued this year with the movies "Armageddon" (on the occasion of the international "Asteroid Day"), "Arrival" and "Gravity" (as the public event of the biennial meeting of the German amateur astronomy association Vereinigung der Sternfreunde), introduced by C. Liefke and M. Nielbock. Our partners at Astronomieschule e.V. also organised a public workshop on astrophotography this year.

The year 2017 also saw three memorable firsts: Classical music came to the auditorium in our "Musikalische Sternstunde," combining classical music by the Blue Planet Music ensemble and a planetarium show (N. Fischer). Our Space Adventure Day ("Abenteuer-Weltraum-Tag") combined science fiction, astronomy, space science and astronautics in an event targeted particularly at families with children. A total of 700 visitors explored a market place of information booths from various am-

Fig. IV.3.1: Snowed-in Haus der Astronomie in January 2017.

Credit: M. Pössel (HdA)


Credit: M. Pössel (HdA)

Fig. IV.3.2: Hands-on demonstration of spectra: sorting spheres by colour at the Haus der Astronomie and Astronomieschule e.V. booth at Explore Science, the science fair produced by the Klaus Tschira Foundation in Luisenpark, Mannheim.

ateur astronomy associations, professional institutions, and science fiction communities and attended planetarium shows, short presentations and movie screenings, as well as main talks by the prominent speakers, including science-of-science-fiction specialist Hubert Zitt and former astronaut and ESA Interagency Coordinator Thomas Reiter. Combined, these on-site events drew an audience of almost 3,200 visitors. Last but not least, in December, HdA played host to the official launch of two astronomy-themed stamps by Deutsche Post. The stamps show the Gaia spacecraft and simulated gravitational waves, respectively (cf. figure III.3.5).

On March 18, the HdA opened its doors to the refugees and volunteers involved in Begegnungs-Café Neckarsteinach, exploring basic astronomy from the perspectives of different cultures.

For particularly interested members of the public and in particular for students at the University of Heidelberg, Markus Pössel (with Knud Jahnke) offered a lecture series "Kosmische Evolution für Nichtphysiker" (cosmic evolution for non-physicists) as an introduction to the methods of astronomy for non-physicists.

As in previous years, the largest external science event we participated in was "Explore Science" on June 21–25, the Klaus Tschira Foundation's five-day family science festival, attended by 45,500 visitors (Figure IV.3.2). HdA staff also gave around 20 public talks in various locations throughout Germany.

The "Einstein Inside" exhibition visited Würzburg, Bonn and Hamburg this year. It includes our model of the Gaia satellite as well as a display element explaining "local cosmology" as the focus of the SFB 881 collaborative research center at the University of Heidelberg.

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 2017 MPIA Summer Conference "Galactic Star Formation with Surveys" brought more than 80 scientists to HdA from July 3 to 7.

Additional conferences this year were the SFB Conference "Piercing the Galactic Darkness. Stellar populations in highly extincted regions of the Milky Way" October 16–19. and the "33. Tagung und Mitgliederversammlung der Vereinigung der Sternfreunde", the annual meeting of Germany's national amateur astronomy organisation, organized by C. Liefke, October 20–22. In addition, 51 smaller scientific and organizational meetings took place in HdA. All in all, more than 1,000 scientists and engineers used the HdA as a place for meetings, discussions, and presentations.

Visualization

The work of HdA's visualization specialist Thomas Müller focussed on several areas. One was visualization support for MPIA scientists. In 2017, this included the adaptation of several visualization techniques tailored to give insight into the diffusion limited planetesimal formation process studied by MPIA PhD student Andreas Schreiber, and a project with MPIA postdoc Juan Soler adapting the line-integral-convolution technique to visualize the 2D galactic magnetic field as revealed by the Planck mission on spherical surfaces given in the HEALPix format. Our in-house planetarium is the ideal projection medium for the presentation of the resulting visualizations.

Visualization collaborations also included an internship (P. Quicker) in cooperation with the Visual Computing Group of Filip Sadlo at the University of Heidelberg and MPIA's PSF Theory Group (Hubert Klahr) on stack-view visualization of 2D particle simulations, and a master thesis (Ramin Safarpour) about vortex visualization for protoplanetary discs. In cooperation with the Visualization Research Center Stuttgart (Sebastian Boblest) and the MPA Garching (Tobias Melson), Müller also developed rendering techniques for visualizing a core collapse supernova, and for a project with Lawrence Berkeley National Lab (Khee-Gan Lee), data sets from the COSMOS Lyman-Alpha Mapping And Tomography Observations (CLAMATO) survey.

Additional projects included an exoplanet orrery for fulldome (planetarium) projection, a fully configurable star map written as a python module, a Java application to visualize the transit method for planet detection, and the prototype for a game to demonstrate nuclear fusion reactions in stellar cores.

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

Fig. IV.3.3: Haus der Astronomie Event Posters, created by the MPIA graphics department.

Credit: MPIA graphics department

magazine Sterne und Weltraum, which is part of the Spektrum der Wissenschaft family of magazines. WIS astronomy is led by HdA senior staff member Olaf Fischer who, with his team of (mostly external) authors created 14 sets of curricular materials helping teachers bring cutting-edge astronomy into their classrooms, kindly supported by the Reiff Foundation for Amateur and School Astronomy.

Our most successful product continues to be "Universe in a Box", an astronomy kit for use with kindergarten or elementary school children (developed by Cecilia Scorza with contributions from Natalie 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 adapted for younger students, and SFB 881-related workshops offered, by Cecilia Scorza.

Since March 2015, HdA has been a partner in the EU-funded Horizon 2020 project EU space awareness, developing educational resources related to the ESA programmes Galileo and Copernicus as part of that collaboration. By the end of 2017, we had produced prototypes of 44 new activities and resources: 15 on the subject of climate change, to be collected in a "Climate Box", 5 dealing with navigation, and 24 on the topic of history of astronomy alongside with a toolbox with hands-on materials (C. Scorza, M. Nielbock).

Over the year, a total of nearly 2,800 pupils and preschool children visited HdA for a total of 162 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: Alexander Ludwig (Bertha-Benz-Realschule Wiesloch), Matthias Penselin (Albert-Schweitzer-Gymnasium Crailsheim) and Martin Wetz (Internationale Gesamtschule Heidelberg).

This year, we developed new workshop concepts in cooperation with Junge Uni Heidelberg (N. Fischer) and for this year's Explore Science (N. Fischer, C. Liefke), all three centered on various aspects of the Sun and its energy production.

In five "Astro Camps," organized by Astronomieschule e.V., almost a hundred young participants stayed overnight on Königstuhl to observe the night sky (or, in unsuitable weather, observe stars in the HdA's digital planetarium).

Fig. IV.3.4: Participants of the German-Italian WE Heraeus Summer School "Astronomy from Four Perspectives: The Dark Universe," held at Haus der Astronomie August 26 to September 2, 2017.

Credit: HdA

Credit: K. Jahnke (MPIA)

Fig. IV.3.5: Going postal: Official unveiling of the new astronomy-themed German stamps at Haus der Astronomie on December 7, 2017. Left to right: Claudia Schäfer (Department Head Stamp Management and Individual Products at Deutsche Post AG), HdA managing scientist Markus Pössel, German member of parliament Karl Lamers, ESA Senior Science Advisor Mark McCaughrean and Gaia DPAC Outreach lead Stefan Jordan.

External events for pupils included the JuniorAkademie Baden-Württemberg in Adelsheim (C. Liefke), with this year's course focusing on volcanism and seismic activity of the Earth, as well as a course at "Deutsche SchülerAkademie" in Torgelow (O. Fischer).

Reaching out to communicators and educators

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

Pre-service training included two seminars (O. Fischer, C. Liefke) and the annual block course "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). In addition, over the course of the years, eight students aiming to become physics teachers were working on their masters thesis (in its German incarnation as "Staatsexamensarbeit") at HdA, with topics ranging from solar observations, the construction of an all sky camera and the transit method for detecting exoplanets to weak gravitational lensing, ALMA and the visualization of exoplanet orbits.

In-service training 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 (O. Fischer), the one-day course "Astronomie und Raumfahrt" for the Baden-Württemberg education ministry (M. Pössel, M. Nielbock and M. Gross). We also hosted the Heidelberg segment of our German-Italian teacher training "Astronomy from Four Perspectives," on the topic of "The Dark Universe," with participants from Heidelberg, Padova, Jena and Florence, again funded by the WE Heraeus foundation (Figure IV.3.4).

For primary school and kindergarten teachers, there were 16 training sessions and numerous consultations. To keep better contact with the participants and to improve our support for teachers bringing astronomy into schools we implemented a local network of primary school teachers (N. Fischer).

External teacher trainings took place in Thuringia (2 days in the Sonneberg observatory) and in Baden-Württemberg (3 days in the state academy for continued professional education Bad Wildbad, as part of a three-year cycle).

This year's mobile teacher training (O. Fischer), supported by the Reiff Foundation, took place in Nordrhein Westfalen and Hessen (Jülich, Hennef, Wuppertal, Dorsten, Lippstadt, Bad Oeynhausen, Wetzlar, Lampertheim) and included for the first time a program for primary school teachers (N. Fischer).

The "Telescope Driver's License" workshop, which qualifies teachers for the use of small telescopes in school, went into another round in November in Adelsheim (O. Fischer, 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 34 telescopes (10 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-friendly conditions on several levels. The University of Heidelberg, one of the HdA partners, is in the process of reforming their physics teacher curriculum. 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, M. Pössel has been involved as an advisor to the Landesinstitut für Schulentwicklung both for the new school subject of IMP (Informatik, Mathematik, Physik) which combines computer science, mathematics, and physics, and includes astronomical content, and for the subject of astronomy itself.

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 42 German high school groups participating in three search campaigns (C. Liefke).

In the field of remote observing (telescopes that can be controlled via the internet; C. Liefke), activity with the Faulkes/LCOGT telescopes focussed on special projects and especially a follow-up program for asteroids discovered by the German schools in the IASC-Pan-STARRS asteroid search campaigns, which finally led to a total of four numberings and thus the right to propose a name for these asteroids by the schools. Just as in previous years, the telescopes were an essential part of the HdA/MPIA Girls' Day program.

In spite of a string of minor technical difficulties, the ROTAT remote observatory was frequently used throughout the year for near-earth asteroid observations and minor planet discoveries. Its telescopes were also used in a research project on exoplanet transits by two high school students. The project was supervised by C. Liefke, and entered into the Jugend Forscht Nordbaden regional science fair contest.

Additionally, a student investigated the level of light pollution in Mannheim and Weinheim within the framework of her Hector Seminar cooperation phase project (C. Liefke).

Our internship program in 2017 once more consisted of two instances of career orientation weeks (BOGY internships, C. Liefke) with a total number of 13 participants. Our three-week International Summer Internship, 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 nine participants from Germany, USA, Turkey, Spain, Lebanon and Pakistan. Furthermore, we had nine interns staying between two and ten weeks throughout the year.

Networking

Internationally, our main collaborations are in the framework of the UNAWE and EU Space Awareness networks as well as part of the DAAD center of excellence in investigation and teaching (astronomy) of the Heidelberg University.

Regionally, we continued our fruitful collaboration with Forscherstation, the Klaus Tschira Center for Early Science Education in Heidelberg. The collaboration includes a joint appointment (N. Fischer) for the development of educational materials and teacher workshops.

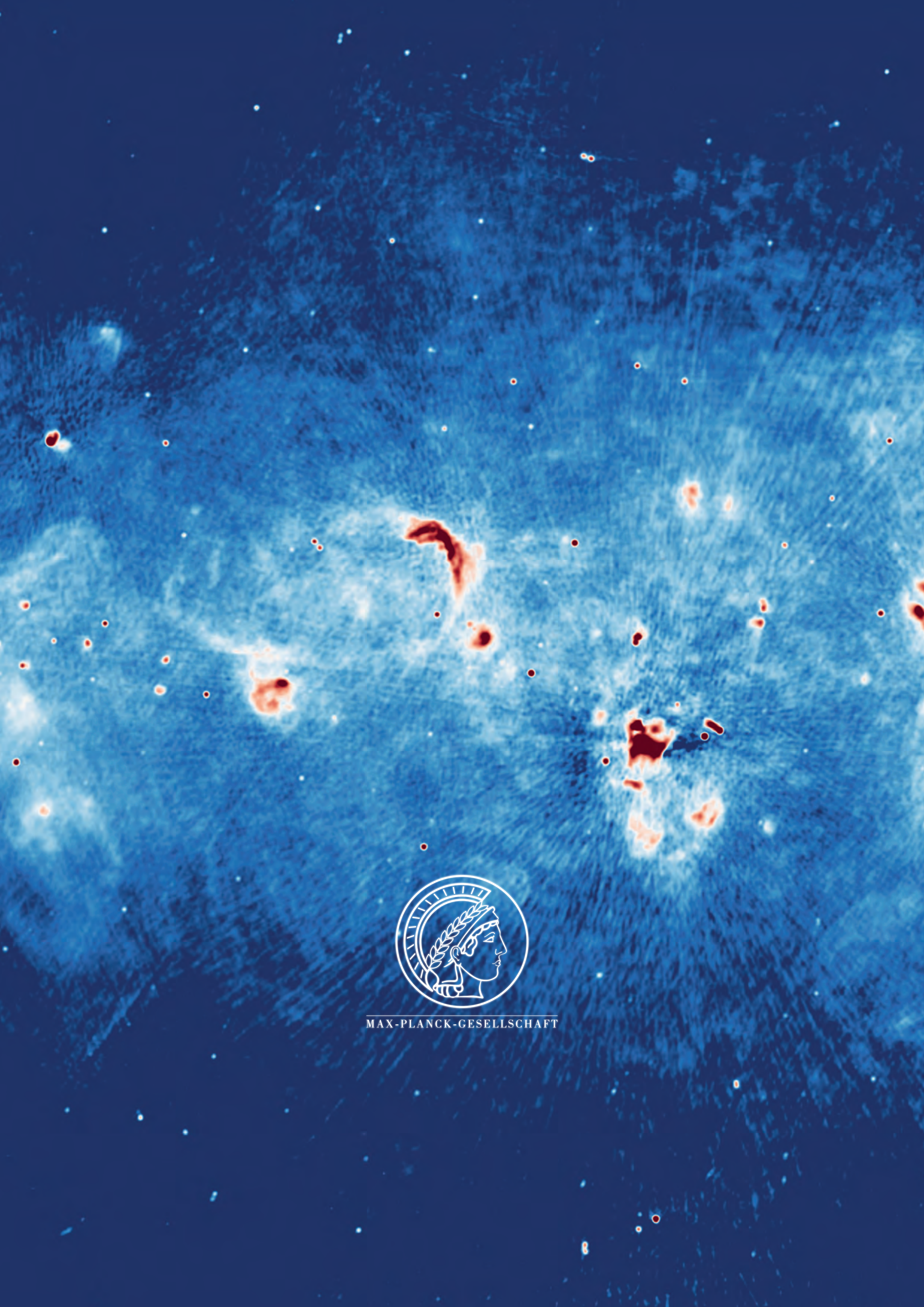
HdA also has a network of partner schools throughout Germany, encompassing 41 schools in 15 of Germany's 16 federal states. Of course, we also collaborate with a number of additional national and international institutions. For instance, there is a fruitful collaboration with Chile, which has resulted in teacher training events reaching (so far) nearly 600 teachers throughout the country over the past two years, from Arica in the North to Puerto Montt in the South, and also in 25 German teachers getting the opportunity to visit the Chilean observatories.

Our collaboration with ESO on the "ESO Supernova" (ES), a younger (and larger) sibling for HdA now under construction, continued with technical consultations in particular about the ES educational program, but also with a contribution to the building's permanent exhibition: a back-lit model of the Milky Way, constructed by Cecilia Scorza in collaboration with MPIA's precision mechanics workshop, representing SFB 881 research.

HdA was also represented at relevant meetings and conferences, including the annual meeting of the German Planetarium Society and the Outreach Meeting at the German Astronomical Society.

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

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