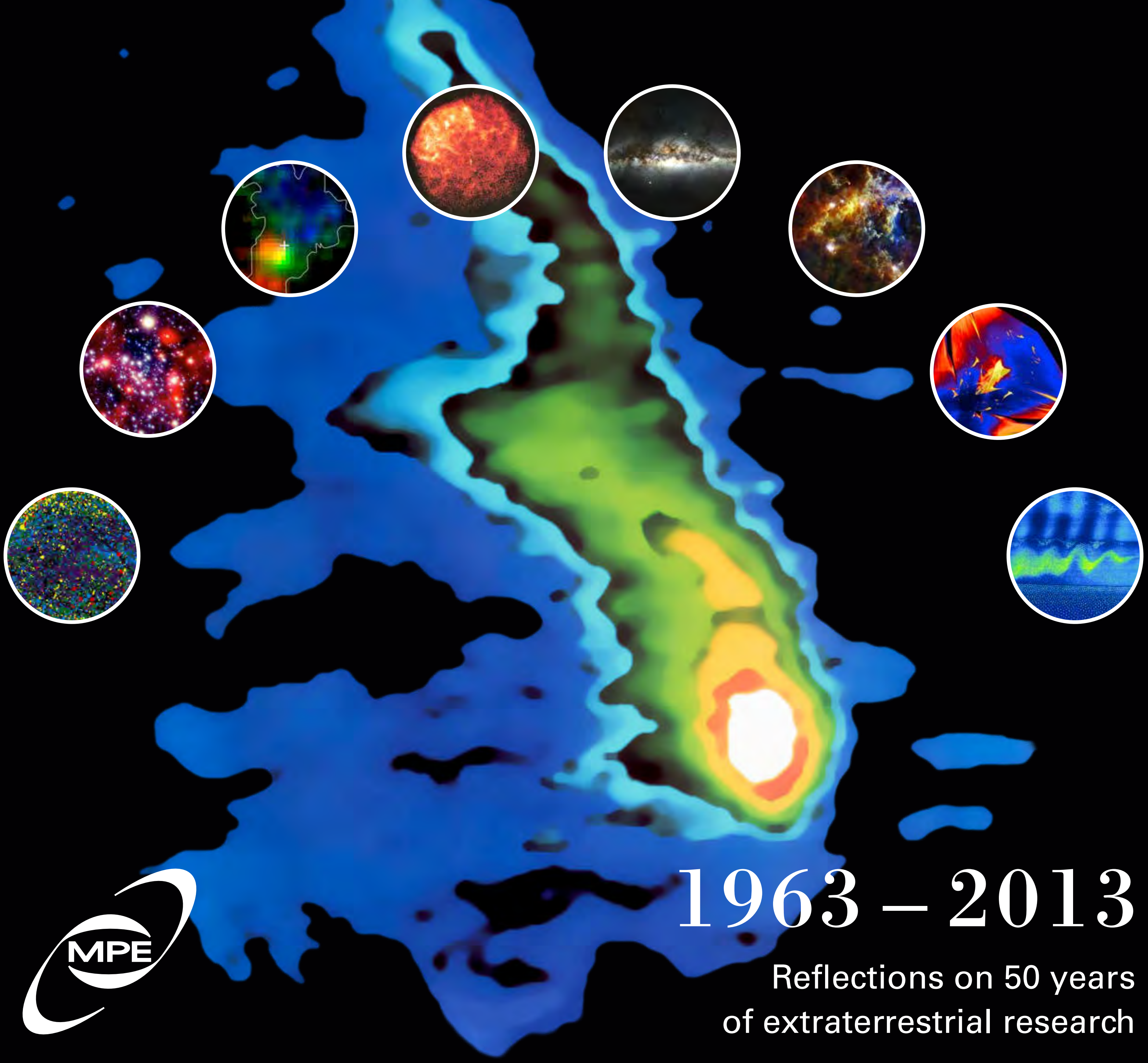

1963 – 2013

Reflections on 50 years
of extraterrestrial research

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1963–2013

Reflections on 50 years of extraterrestrial research

MPE
Max-Planck-Institut für
extraterrestrische Physik

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PREFACE

The golden jubilee of the Max Planck Institute for Extraterrestrial Physics is an excellent opportunity to celebrate: for current MPE institute members, former colleagues, and partners from many institutes and companies in Germany, Europe and all over the world. The MPE started as a small group in 1963 and has now grown into one of the largest institutes of the Max Planck Society, with scientists, engineers, technicians and administrators working closely together to push forward the frontiers of our understanding of the universe; the stars, galaxies and everything else that it contains.

Commemorating this anniversary, the institute is looking back on what has happened over the past 50 years. While science has always been at the forefront for all endeavours of the MPE, we also wanted to tell the story behind the science, through the eyes of the people who have contributed to it.

This is not a history book. It was written neither by a historian nor by a scientist. The tales recounted in this book put a spotlight on many projects, big and small, but also tell little anecdotes that were funny, scary, surprising or simply amazing. And while I hope that you will enjoy browsing through this book, there are many who will be disappointed that some topics have been omitted. The institute has worked on so many projects and in so many different fields that it would never be possible to do all of them justice. My apologies to all that were not mentioned and my deepest thanks to all who contributed to this book by providing photos, recounting incidents, and in general spending time and effort to make this a success.

We hope that we were able to capture the spirit of the MPE and give an impression of what it means to be part of its adventure. To all "MPEler": This book is for you.

Hannelore Hämmerle
Writer & Editor

MPE'S FIRST 50 YEARS

Reimar Lüst

The roots of the MPE story go back to 1950. At that time I, as a Ph.D. student, attended the lectures on comets by Ludwig Biermann. There he claimed that solar corpuscular radiation (later called solar wind) triggers the ionized cometary tail. The story continues even more remarkably in that twelve years later at the end of 1960 Werner Heisenberg and Ludwig Biermann, the Directors of the Max Planck Institute of Physics and Astrophysics, asked me as a theoretician to build up an experimental working group on space research within the institute.

I was very lucky that within a few months I was able to form a small group of enthusiastic physicists, engineers and technicians whose task it was to prepare experiments in space. Without any experience we started our first sounding rocket experiment from the Île du Levant in the south of France in November 1962 with the help of the French space physicist Jacques Blamont. Unfortunately the rockets were not successful.

But this did not prevent the Senate of the Max Planck Society from deciding, in 1963, that our small group should become a new Max Planck Institute within the Max Planck Institute of Physics and Astrophysics.

In the coming years quite a number of people helped to build up the institute. Very soon it expanded its activities from the artificial plasma-clouds to particle experiments on satellites and in particular to the field of gamma-ray astronomy. Klaus Pinkau joined the institute in 1966 to build up the latter activities, while Gerhard Haerendel became the driving force for the plasma experiments.

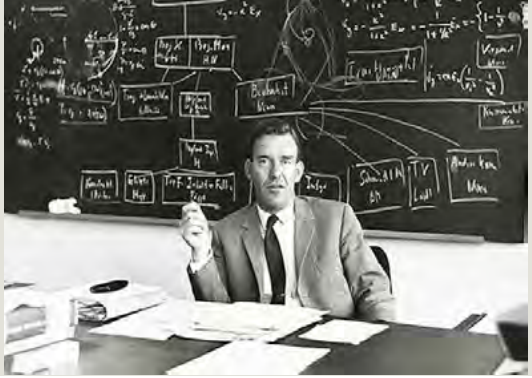
In 1963 construction started on the first building, which was financed by a special fund, and it was inaugurated at the beginning of 1965.

Prof. Auger, Director General of the European Space Research Organization, ESRO, gave the ceremonial address. At that time I regarded the building as much too large but I very soon found out that we needed an expansion.

Now MPE has grown into one of the largest Max Planck Institutes, with more than 400 people designing cutting-edge astronomical instrumentation and working on a wide variety of topics. While in the beginning we focused on exploring the immediate surroundings of Earth with rockets, this was soon complemented by satellite missions to study the high magnetosphere. In the following decades, extraterrestrial astronomy increasingly gained in importance, being studied at wavelengths ranging from the highest energies to the infrared regime. The space-based observations and experiments are now complemented by large endeavours on the ground, which are absolutely necessary for research at the frontiers of astronomy.

Even though I had to leave the institute in 1972, when I became President of the Max Planck Society, I have always kept an eye on “my” institute and I am very proud that we can look back on 50 years of exceptional space research. My congratulations to everyone who contributed to this success, which has only been possible because of the dedication and efforts of all the people involved. I wish the institute all the best and many challenging open questions for the next 50 years!

REACHING FOR SPACE



← MPE’s founding director Reimar Lüst.

↑ The popular “Kaminabend”: Herr Breukel, Herr Föppl, Herr Neuss (from left).

BEYOND THE ATMOSPHERE

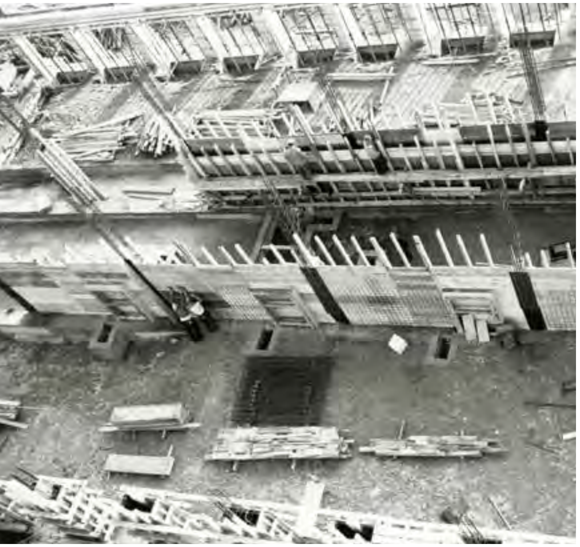
Ulf von Rauchhaupt

At first glance, the process of MPE’s foundation looks simple indeed: On 15 May 1963, the senate of the Max Planck Society (MPG) conferred upon a small research group of some 15 people the status of a third institute within the Max Planck Institute for Physics and Astrophysics in Munich. The group’s leader, Reimar Lüst, was appointed as director. A new research field (extraterrestrial physics) had opened up; MPG decided to join in, and chose an eminent scientist to build the institute around.

Extraterrestrial physics is determined by its means of research rather than its objectives. A few years before MPE came into being, those means suddenly experienced a qualitative improvement beyond measure. Then, in the wake of the Second World War, a technology was becoming available that promised a new dimension to science: rocketry. Among the first scientific aims of rocketry was to attain knowledge about the higher layers of the atmosphere, the ionosphere and the region where the gas cover of our planet continuously merges into space. To promote the “peaceful application” of the new technology during the next solar maximum, the International Geophysical Year was proposed for 1957/58.

←← The first “extraterrestrials” in front of the Garching barracks in 1961: Hans Neuss, Frl. Hartmann, Erika von Stabel, Berhard Meyer, Hans Heinz Rabben, Werner Göbel, Herbert Bause.

→ The shed built in 1961 for the Institute for Plasma Physics was passed on to the newly founded MPE in 1963. It provided 286 m² of office and lab space.



←→ The young institute required more space: construction of a new building of 1200 m² on three levels started in 1962. The first MPE staff moved into their offices in 1964 and the official inauguration was celebrated on 15 February 1965.

→ In autumn 1966, construction of an extension building started, housing laboratories and workshops, which was operational in late 1967.

“The first project was an artificial comet”

A couple years later, in March 1960, the MPG established a working group in Munich to discuss potential topics for extraterrestrial research in Germany. Among the themes specified were the ones undertaken abroad at this time – especially in the USA. Top of the list were radiation belts and cosmic rays as well as their interaction with the terrestrial magnetic field. Others were solar activity, X-ray and UV-astronomy, reduction of (foreign) satellite data and upper-atmosphere research with small sounding rockets. This reads like an account of the research fields later covered by the MPE in the mid-1960s and afterwards – although the weighting has shifted considerably. But for the time being the founding fathers were not quite explicit about where they should actually start. Whatever this would be, 100,000 DM in the first year and a wooden cabin in Garching to work in were considered sufficient.

The first project of the new extraterrestrial work group was an “artificial comet” to probe the solar wind. It was new, but comparatively inexpensive. It was simple, but theoretically interesting. It was plasma physics and it was in space – thus eligible for the funding available then. The final goal, however, was interplanetary space – which could only be reached with the most powerful launch vehicles of the time.

On the very day that the MPG senate approved the creation of MPE, on 15 May 1963, the institute’s first successful experiment flew from a French launch pad near Hammaguir in the Algerian desert. A load of barium was evaporated to form a cloud at a height of 155 kilometres. At this early stage of development, the technology of generating ion clouds was

← The Centaure rocket with its ion cloud payload on the launch pad in the Sahara desert in 1964.

↑ Celebration in the institute's garden, around 1970.

↖ Official inauguration of the new MPE building with MPG President Adolph Butenandt (second from left).

↑ The "extraterrestrische Konzil" provided the opportunity to discuss science and get together in a relaxed atmosphere, such as here during the first council at lake Tegernsee.

thoroughly tested in the more easily accessible part of space right above the Earth's atmosphere.

The instrumentation – much more than the subject – distinguishes MPE from other institutions with research interests in the sky. This instrumentation was and is flown on a choice of platforms: balloons and rockets in the first decades, satellites and space probes until today. Legally, MPE remained a sub-institute of the Physics institute until 1991, when the Max Planck Institutes for Astrophysics (MPA), for Extraterrestrial Physics (MPE) and for Physics (MPP, now named after Werner Heisenberg) officially became independent institutes.

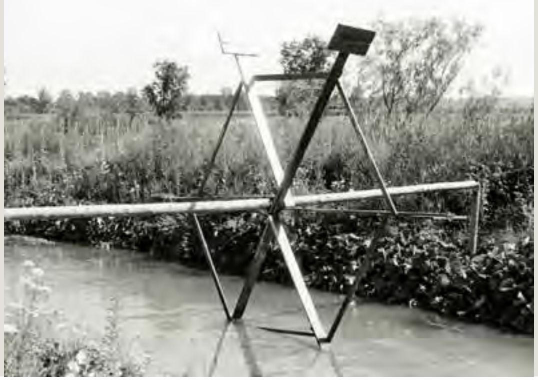
(Based on an article about the political framework and the foundation of the institute that appeared in 2000 in the US spaceflight journal, QUEST, Vol. 8, No. 2, pp. 32- 44.)

TEAMING UP

Jakob Stöcker

Life at the institute consisted not only of research but was complemented by social activities that were important for all the staff members, from the directors to technicians. Especially during the first years and decades, when the institute's staff complement steadily grew to 100 and more, there were festivities on many occasions: a completed doctoral degree, carnival, summer, the inauguration of a new building, or whatever other reason could be found.

Good camaraderie was essential especially for the balloon and rocket campaigns, when sometimes half of the institute, including technicians, secretaries and assistants, went on trips that lasted for weeks. Such a large crew was necessary both to maintain the instruments flying in the payload and to operate the observing gear at the different stations. While



↑ For the summer party, the organisers wanted to roast a large piece of beef on a spit. And since the MPE was an experimental institute, the engineers found an appropriate solution: the skewer was turned with hydropower using a home-made water wheel.

↑ Reimar Lüst at the Oktoberfest.

↑ Body vs. Brain. In these football matches even MPE directors participated, either as referees or active players.

↑ Taking his leave, Klaus Pinkau (right) celebrates with Joachim Trümper (left) and Arnulf Schlüter.

↑ Reimar Lüst (centre) in discussion with MPE staff members.

↑ Model of the MPE extension building across the river (inaugurated in 2000).

the accommodation and provisions during the trips were often quite basic, the groups were welcomed exuberantly on their return to Munich airport – performances by the MPE in-house Dixie band included!

Sport also played a big role at the institute, with regular skiing, hiking or sailing excursions and annual tennis and football tournaments. Here the teams named Body (technicians & co) and Brain (physicists and engineers) competed against each other with absolute dedication and never a foregone conclusion about who would win.

Once a year, the scientists and engineers would come together for the "extraterrestrische Konzil" to discuss important new scientific results during the day, and what direction the institute should take for the future in the evenings. In the beginning, this was hosted by Reimar Lüst in his house and garden at lake Tegernsee, but soon this venue became too small and the council went to various locations before it eventually found its home at Schloss Ringberg, the Max Planck Society's new convention centre.

The scientists and engineers have always worked closely together to find the best solutions for the scientific tasks at hand. During the weekly "Institutskaffee", problems were discussed – and not only scientific ones. Everybody would share their expertise and if a new idea emerged – even if it was unconventional – more often than not it was given a try. This is why the latest MPE extension building now straddles the river passing through the Garching campus, rather than being appended on the other side of the "old building".

THE FIRST YEARS

↑ On the way to Île du Levant, where the first rocket experiment with ion clouds took place. Some boxes with equipment and Herr Melzner on the roof of the car.

EXPLOSIVE ROCKET MEN

Erich Rieger

This is how it started: a group of scientists including Ludwig Biermann, Reimar Lüst and his wife Rhea Lüst got together at the MPI for Physics and Astrophysics and thought about how they could create an artificial comet. This would help them to better understand the "solar wind", a steady stream of particles emitted by the Sun. The elements to be used had to have certain characteristics, such as resonance lines in an optical wavelength that could be observed from Earth, a low ionization potential so that they could be ionized by solar UV radiation, and it should be easy to vaporize them, i.e. to form a gas cloud.

Therefore a lot of effort was dedicated to producing chemical mixtures that would produce metallic vapour in an exothermic reaction. How dangerous this could be was impressively demonstrated when a ball mill used to pulverize aluminium and barium was destroyed in a violent explosion. Even though the mill was fitted into a concrete sewer cylinder for safety reasons, the explosion was so powerful that tools were shaken from the walls of an adjacent shed. Nevertheless, in the end the team found the correct recipe and performed tests with several mixtures on the ground and under vacuum conditions.

←← Cameras for observing the ion clouds were set up at different stations, such as here at Colomb Bechar in the Sahara desert.

← The rocket observation campaigns also provided the opportunity to explore the surrounding countryside. Sometimes, however, the adventurers had to make unplanned breaks, such as here waiting for help after the car had a flat tyre.

In November 1962, almost the whole team went to Île du Levant in southern France. Here, two French Centaure rockets were launched with containers loaded with an aluminium-barium mixture – marking the first shot for extraterrestrial space. Unfortunately, both rockets had to be destroyed soon after take-off, but the later campaigns were successful.

Several rocket launches followed, both in Sardinia with Skylark rockets and in the Sahara with Centaure rockets. The first successful barium ion clouds were produced on 27 November 1964 when a rocket from Hammaguir in the Sahara desert brought the metal mixture to a height of 150 km. The rocket had to be launched just after sunset, so that the ion cloud would still catch the last solar rays. At the same time the sky had to be dark enough so that the observers on the ground near Colom Bechar and Beni Abbes could observe the pale cloud with their cameras and spectrometers. And indeed: in addition to the green line of atomic barium, the astronomers saw four intense purple lines of ionised barium. This was the first step towards an artificial comet!

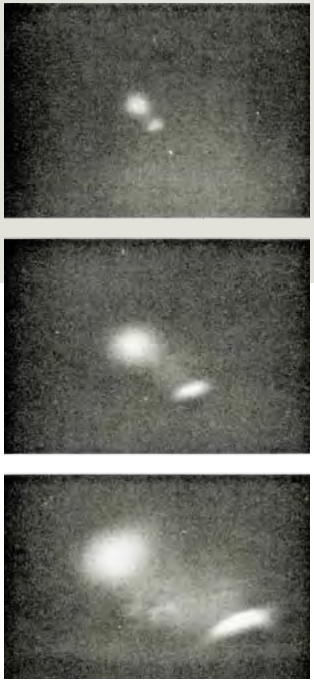
In addition to finding the optimum barium mixture, the group also started to design experiments to measure the electron density and the highly energetic particles of the radiation belt. Again, the rocket for the Rubis experiment was launched in the Sahara desert. The expedition to the oasis Ti-in Misaou, which had been selected as the observation point was accompanied by French troops, which meant excellent provisions even though the accommodation was somewhat primitive. And when one of

↓ Observation cameras for a Centaure ion cloud experiment.

← The Rubis experiment launched in 1966 not only included a barium container but also some instruments to measure electron and particle densities in the lower magnetosphere.

→ The Rubis rocket before start.

↓ The Rubis MPE team.



← The first ion clouds observed on 27 November 1964 over the Sahara desert: the elongated barium cloud and the round strontium cloud 164 seconds, 213 seconds and 745 seconds after vaporisation. It was very surprising that the barium cloud was so compact, which meant that the ionisation of barium occurred much faster than anticipated; it took less than a minute rather than the expected quarter of an hour.

the French colleagues found some stones that had undoubtedly been worked by humans, the astronomers turned into archaeologists for a short time: among their finds were pieces of broken bowls, hand axes and other shards made of granite or other hard materials as well as some petroglyphs that were close to the oasis.

When the rocket was launched on 22 April 1966, the weather at both observation stations was excellent. And not only there – most of Europe also had good weather conditions. Thus many people saw the strange luminous clouds in the sky. However, no one could guess the correct reason behind them, not even some astronomers who were out for a late stroll after their conference sessions in Vienna. Some might even have worried that aliens had come to Earth – but it was only the "extraterrestrials" from Garching, who were conducting their experiments in the lower magnetosphere!

↑ Because of the explosive mixtures used in the barium containers, small fires or explosions occurred from time to time. This, however, was nothing compared to the fire in the original MPE barracks just before Christmas 1970 – though the reason for this was probably a short circuit in the attic and not the ingredients for the experiments.

"Strange luminous clouds in the sky"

↑ Sign on Stuart Highway, which passes through the Woomera Prohibited Area, South Australia, one of the launch sites for MPE's rockets. The area was originally established after the Second World War to support a rocket testing programme. Woomera is named after an Aborigine weapon of the same name, a spear-throwing implement, which extends the spear's range.

← Preparing for ion cloud observations in 1966: Hans Neuss, Reimar Lüst, and Gerhard Haerendel.

EXPERIMENTING ABOVE THE ATMOSPHERE

Gerhard Haerendel

The first experiments in space produced spectacular results. The barium ion clouds immediately showed the direction of the magnetic field; and for the first time the plasma motion of the ionosphere (rather than neutral air) became visible. Having the capability to measure plasma motion or electric fields, the ion group increasingly went to "geo-interesting" regions, both close to the polar circle and near to the equator. The aim was to study the interaction of the ion clouds with the auroral plasma or with the equatorial anomaly, respectively, and thus learn more about the Earth's magnetic and electric fields as well as typical plasma instabilities occurring in these regions. Excursions therefore went to locations such as Fort Churchill (Canada), Kiruna (Sweden), Thumba (India) or Woomera (Australia).

From 1967 onwards, the MPE group became more independent with a mobile rocket launch pad of the German Space Centre (precursor to DLR) and diversified its campaigns with more elaborate analysis instruments flown on the rockets. In addition, satellites such as HEOS A1 were used

←← The ion cloud experiment was mounted on the mobile Nike Tomahawk rocket and launched from Wallops Island, USA.

← The SCOUT rocket was used for experiments in the high atmosphere.

↑ Dual Hawk rocket in Thumba, India, 1972.

↑ The second Porcupine experiment was launched successfully with an Aries rocket in 1977.

→ The AMPTE satellite was brought to orbit by a Delta Rocket from Cape Canaveral. In late 1984, it produced the first man-made, artificial comet.

↑ Members of the ion cloud group in Kiruna, Sweden – all coordination with other observing groups had to be done by telephone.

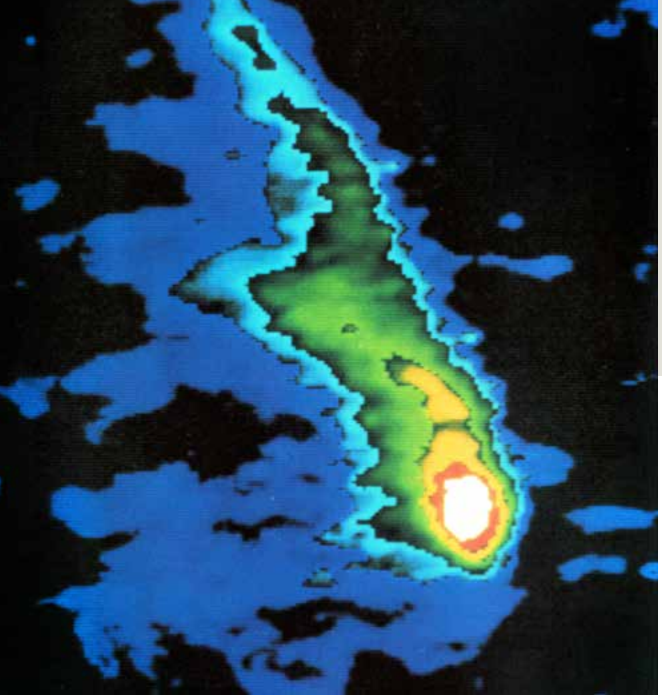
← The ion cloud produced by the HEOS satellite.

↓ The core of the rocket payload: four containers with an explosive aluminium/barium mixture. (Thumba, India, 1968)

and on 18 March 1969, an ion cloud could be observed at a distance of more than 70,000 kilometres, nearly 12 Earth radii. At this distance the magnetic field is relatively small, and the "dense" ion cloud actually produced a diamagnetic void, which dissipated in a matter of minutes. Directional changes of the strongly elongated cloud showed some connection between the plasma currents in the magnetosphere and those in the ionosphere. A similar experiment with a Scout rocket at a height of 5-6 Earth radii produced a cloud which broke into many spectacular parallel streaks. It took several decades and careful reanalysis of the data to find the correct physical interpretation of this behaviour: the paper describing the "MI-coupling" was published some 40 years after the experiments took place!

With so many campaigns over the years there were naturally also some disappointments. One dramatic incident was the loss of the "Porcupine" mission in 1976, when the Aries rocket carrying it into space exploded just before burnout. This had never happened to the Minuteman system, from which the Aries motor was obtained as a surplus. So the big question was: what was different this time? In an intense meeting in Las Vegas, the MPE researchers and some aerospace engineers discovered that, because of the relatively light payload, the rocket went much faster, leading to enhanced internal convection. Consequently the hot gas inside the rocket motor eroded the insulation layer too fast, which led to the explosion. Once the problem was identified, a solution was quickly found and a "heat sink" was developed to drain off the excess energy.

← The completed AMPTE satellite during vibration tests.



← First artificial comet, 4.4 minutes after injection into the solar wind. The tail of several thousand kilometres in length and the sideways extracted ions are clearly visible.

This heat sink was then used for many other missions, in particular on three successful "Porcupine" rockets. Aptly named, this plasma experiment included many spikes housing different analysis instruments as well as four containers of barium for ejection.

Because shaped charges produced fast ion beams that travelled to very high altitudes along the magnetic field, these were a particularly promising tool for auroral research. In one experiment started from Greenland, the auroral acceleration process was actually made visible. The timing of the ion injections was crucial, as many associated ground observations had to be coordinated. These were spread across several countries, even including aircraft-borne TV cameras. This meant close monitoring of the weather forecasts and auroral conditions and lots of telephone calls (internet and emailing only being in their infancy back then). For the most elaborate observation campaign, about a dozen different camera stations in Europe and the Soviet Union worked together.

Finally in 1984, the AMPTE satellite produced the very first artificial comet in space, 25 years after the first idea of Ludwig Biermann and a couple of years before the natural comet Halley made its Earth flyby. On 27 December, within four minutes, a barium cloud consisting of 2 kilograms of barium ions grew – with the help of the solar wind – a long tail of which more than 10,000 kilometres in length could be observed. Surprisingly this showed that during the first few minutes the head of the artificial comet did not move with the solar wind but rather perpendicular to its direction of flow. This recoil effect was due to the extraction of barium ions by the interplanetary electric field.

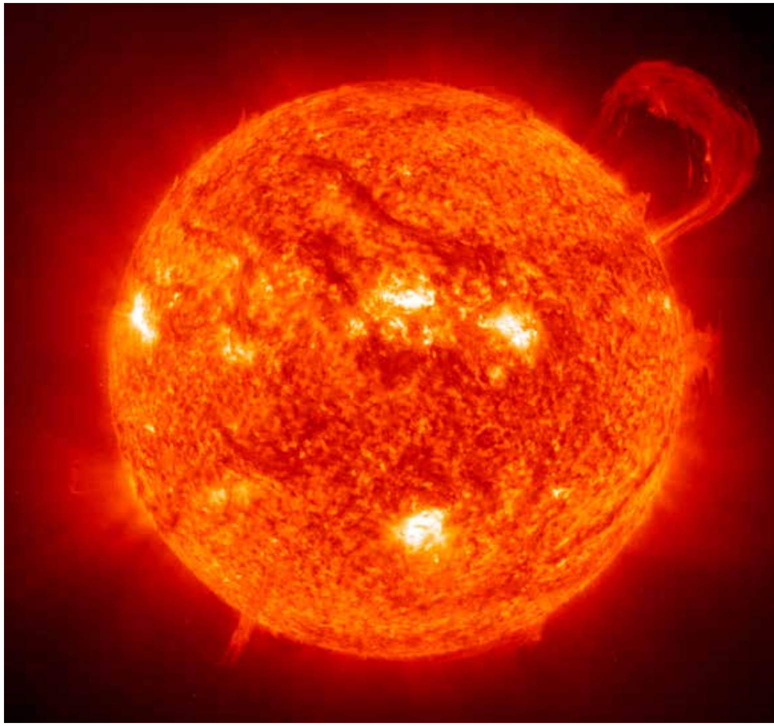
Two decades of ion cloud experiments supported by in-situ plasma and field diagnostics not only led to many new insights into plasma physics, the solar wind and the Earth's magnetosphere, which were published in more than 1000 scientific papers. With these experiments MPE also gained valuable experience and expert knowledge in designing and preparing space missions in general, paving the way for many other projects.

← Measurements of the magnetic field and the energy distribution of protons and electrons above the Earth's atmosphere from the HEOS satellite and observations from the ground.

SOLAR-TERRESTRIAL RELATIONS

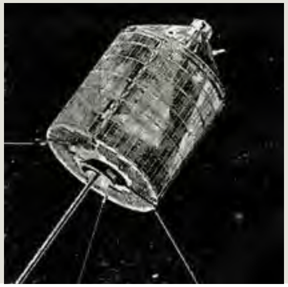
Berndt Klecker, Götz Paschmann, Manfred Scholer

The Sun not only sends us light and warmth, occasionally there are gigantic flares that emit high-energy particles into space. For simultaneous measurements of the mass, the energy and in particular the electrical charge of these particles, MPE ventured into new areas of science and technology: existing proportional counters and solid state detector systems had to be combined with an electrostatic deflection, which had never been attempted before as the detectors were either too heavy or too large to fit on space-borne instrumentation. However, with the experience gained when developing instruments for Germany's first mission in space, AZUR, as well as advances in sensitivity and resolution, the MPE team successfully developed novel detector systems for a number of space experiments – and established a reputation for constructing large instruments in-house rather than contracting them out.



↑ The level of solar activity varies considerably, sometimes there are large active regions developing into flares and huge coronal mass ejections, spewing high energy solar particles into space.

One of the first discoveries however was not about solar particles but rather an "anomalous" component of cosmic particles due to their composition: there is almost no carbon in contrast to solar and galactic



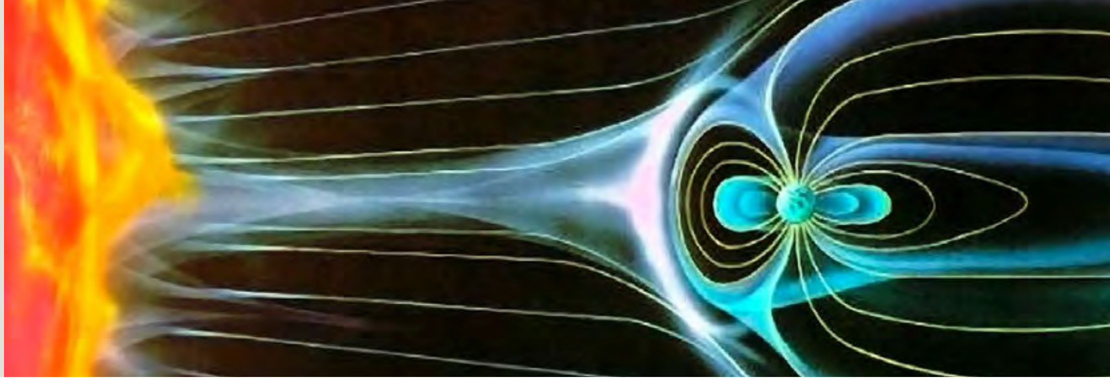
← The first German spacecraft AZUR, launched in 1969.

← The SOHO spacecraft was launched in 1995 with twelve instruments to study the Sun's interior, its visible surface and atmosphere as well as energetic solar particles – and is still in operation today.

cosmic rays. Because of the abundance of elements the scientists soon suspected that this anomalous component was due to neutral particles from interstellar space that were ionised in the inner solar system and picked up by the solar wind. If so, these ions would only be singly ionised – a hypothesis that was proven thirty years later.

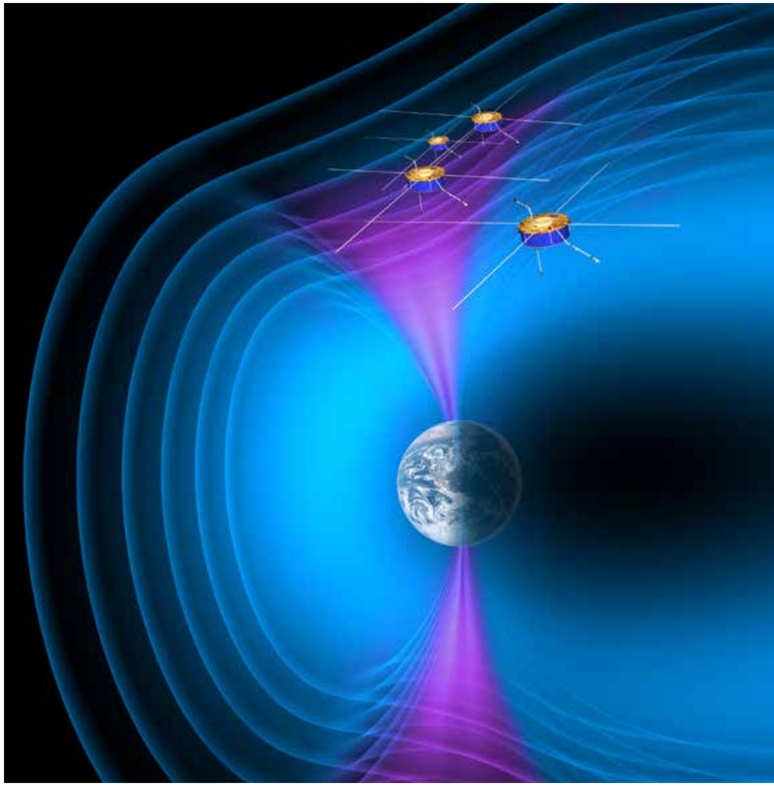
But also with respect to the solar particles themselves the scientists were in for a surprise. The charge of the solar particles is an indication of temperature: the higher their ionisation, the hotter their original surroundings in the Sun's corona. However, in the solar particle events directly related to flares, the charge and energy of the particles turned out to be correlated. As there is no physical process in the higher levels of the Sun's atmosphere that could lead to such a correlation, the particles in these events had to originate from further inside the Sun's atmosphere than had been assumed previously, where the dense surroundings of the particles strip off some of their electrons.

← The two Helios spacecraft launched in 1974 and 1976 were a very successful German-US collaboration to study interplanetary magnetic fields and particles.



↗ EQUATOR-S was a low-cost mission designed to study the Earth's equatorial magnetosphere out to distances of 67,000 kilometres.

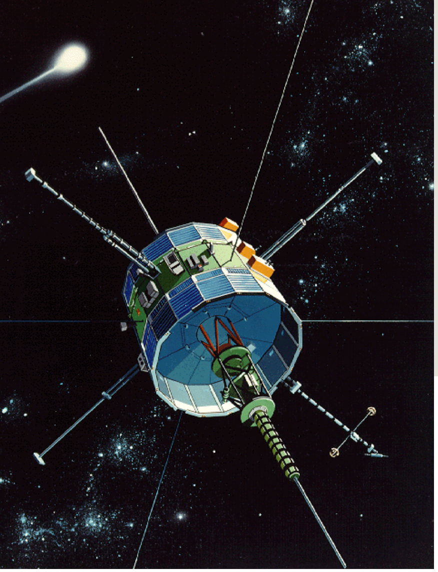
↑ The Earth's protective magnetic shield is compressed by the solar wind – a bow shock develops.



↑ The four Cluster spacecraft fly in an elliptical polar orbit and have provided a detailed three-dimensional map of the magnetosphere, with surprising results. MPE contributed the electron drift instrument for precise measurements of the ambient magnetic field.

Closer to Earth, the scientists have investigated the interaction between the solar wind and our planetary magnetic field: the magnetosphere, which consists of a compressed magnetic field in the direction of the Sun and a long tail on the night-side of the Earth. Detailed measurements revealed a bow shock that exists in front of the magnetosphere, where most of the energy of the supersonic solar wind is converted into heat in a collision-less process. Some of the particles are turned back into the shock and can reach high energies due to multiple interactions – a process that occurs on much larger scales in other astrophysical settings.

On the outer boundary of the magnetosphere, the magnetopause, the terrestrial and the interplanetary magnetic fields merge. In-situ measurements here and also in the long tail provided new information about plasma flows and currents, as well as smoking-gun evidence for magnetic reconnection. Electrons are accelerated along the Earth's magnetic field and cause the spectacular display known as aurora, when they strike the



↖ The International Sun/Earth Explorer 3 was originally placed in an orbit around the first Sun-Earth Lagrangian point, at a distance of about 1.5 million kilometres from Earth. The seemingly relaxed atmosphere during launch is deceiving …

upper atmosphere. Extensive numerical simulations have been carried out to understand the plasma processes in these regions better and to provide the context in which to interpret the observations – completing our view of the outmost layers around Earth.

When the solar observatory SOHO started in December 1995, the MPE instrument team and their colleagues eagerly awaited the start-up of their CELIAS detector in the NASA control centre. The first command was sent up to the satellite to open the protective cover – but seconds turned into minutes before finally the indicator light turned green and the scientists could breathe easily again. The opening mechanism was based on paraffin wax that had to be heated by an electrical current, but as the ambient temperature at the satellite's orbit was lower than assumed, it took longer for the paraffin to heat up. After this initial scare, however everything was ready for many more years of studies of solar particles!

HUNTING FOR THE HIGHEST ENERGIES

↑ The Compton telescope launch in 1974 …

↗ … and at a height of 40 kilometres, where the balloon has a diameter of about 100 metres.

FROM BALLOONS TO SATELLITES

Volker Schönfelder

Once the first successes were realised with the ion cloud experiments, MPE wanted to diversify the science being done at the institute and started working on gamma-ray research under its new director Klaus Pinkau. Gamma-ray astronomy was then a very young field where first activities had just begun to yield results. (The first cosmic gamma rays were observed in the late 1960s). However, not only the field was young – many of the scientists involved were still quite junior but they were nevertheless given responsibility (and money) even for larger experiments.

MPE had already done some work with spark chambers and continued these experiments with several balloon campaigns. In addition it started a new project to measure neutrons emitted by the Sun's and the Earth's atmospheres; for this new method, double particle scattering was used. By concentrating on neutrons that scattered twice within the spark chamber, the scientists could reconstruct not only the energy but also the direction of the cosmic particle – but it was very difficult to measure.

←← The Compton Gamma Ray Observatory was launched in 1991 on board the shuttle Atlantis.

The method of choice for X-rays was the photoelectric effect; for high-energy gamma rays, the principle of pair production was used. Both included information about the energy as well as the direction of incoming radiation. However, for the range in-between, the lower energy gamma rays, Compton scattering was being used until then, which only made it possible for scientists to measure incoming radiation crudely; the information about the direction of the radiation was lost – this range was called the "impossible range" in astronomy. The idea of "double Compton scattering" was thus deemed quite interesting, since it made it possible to measure the direction as well, and a small budget was provided by the institute to "see how far you can get with it".

The basic principle had to be demonstrated with balloon flights, which were relatively cheap and easy to repeat. Because of the harsh conditions that the instruments were exposed to during the flight – or rather at the end of it – they had to be quite sturdy, and were surrounded by a metal frame.

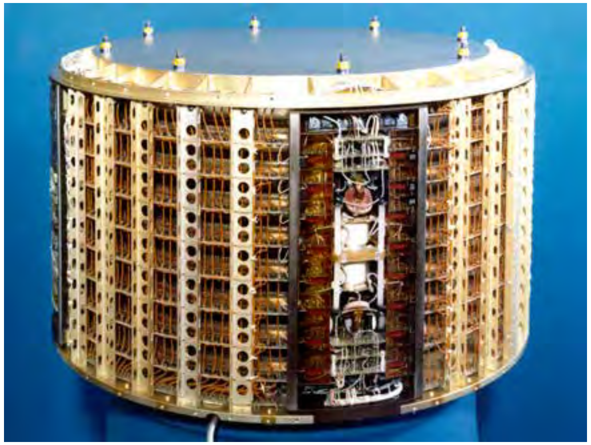
↓ The Double Compton experiment was flown on a balloon to take the first measurements in the "impossible range" and to test the measurement method for later use on NASA's Compton Gamma-Ray Observatory satellite mission.

← Determining the centre of gravity of COS-B.

For the launch the whole structure was suspended on the back of a small truck and hooked up to the balloon trailing the vehicle for up to 100 metres. Once the balloon was filled with helium gas it started to rise; and then came the tricky part: the truck had to drive in the direction of the wind to make sure that the balloon was rising directly above the experiment. But often it was buffeted by the wind and had to be stabilised by hand-held ropes – sometimes quite an adventure!

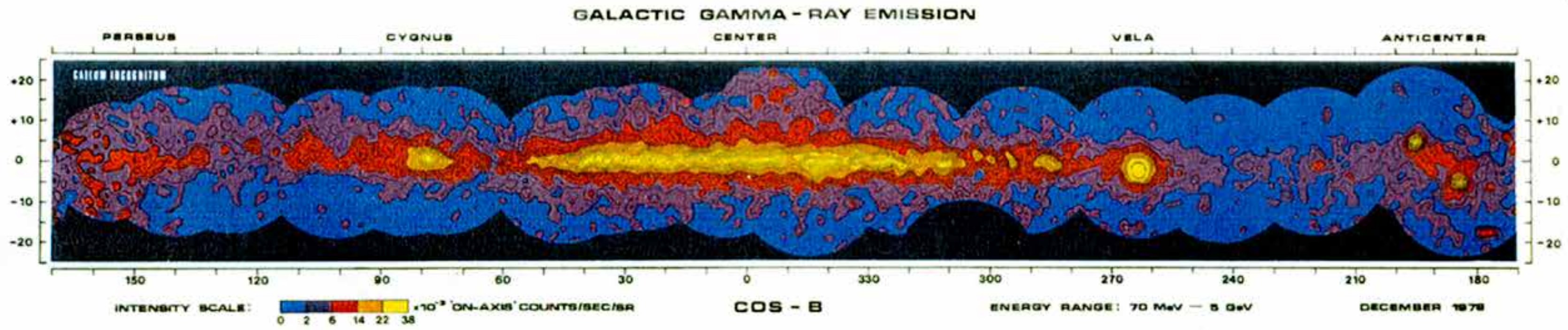
Once the load was released, it would fly to a height of up to 40 kilometres to take measurements typically for 10 hours – sometimes less, sometimes more. A small detonator then separated the balloon from the experiment, which floated back to Earth on a parachute. Most of the time this procedure worked (even though the detonator once went off prematurely and caused the experiment to crash) and the instruments could be reused after some minor repairs.

With these first balloon campaigns of the high-energy spark chamber experiment and the double Compton scattering experiment, MPE succeeded in detecting cosmic gamma rays for the first time. And what is more, they also provided invaluable experience for the following larger satellite campaigns, such as COS-B and later EGRET and COMPTEL on NASA's Compton Gamma-Ray Observatory. COS-B, for which MPE contributed the scientific payload, took measurements for more than six years – three times its foreseen lifetime. It produced the first complete gamma-ray map of the Milky Way disc. In addition, it also found about 25 extragalactic gamma sources (only a handful of gamma-ray sources were known prior to COS-B) and a special focus was put on studying the gamma light curve of the Crab pulsar. The big success of COS-B heralded the start of the golden era of gamma ray astronomy, with MPE being involved in many of the subsequent projects.



↑ The COS-B detector was designed at MPE.

↓ The first map of gamma emissions from our Milky Way galaxy.



← The Gamma Ray Observatory was the heaviest scientific payload ever put into orbit. MPE contributed two instruments: COMPTEL and EGRET.

Schematics for the ↑ COMPTEL and ← EGRET instruments.

WITHSTANDING PRESSURES

Gottfried Kanbach

The heaviest astrophysical payload ever flown, the Compton Gamma Ray Observatory CGRO was one of the four “great observatories” of NASA. It was launched on 5 April 1991 aboard the space shuttle Atlantis. For the 16-ton observatory, MPE provided essential systems for two of the four instruments: the imaging Compton telescope COMPTEL for lower gamma energies and the Energetic Gamma Ray Experiment Telescope (EGRET) for the highest energies. This observatory accomplished the first

← Klaus Pinkau (centre) with a model of the CGRO in discussion with Volker Schönfelder (left) and Gottfried Kanbach (right).

complete survey of the sky in the full gamma ray range and found about 300 sources. Both instruments were built with MPE participation and resulted from international collaborations with scientific and industrial partners that worked very well from beginning to end – as did the instruments themselves.

As the leading "Principal Investigator" institute, MPE was responsible for the overall integration and tests of the COMPTEL instrument, as well as the lower detector assembly and anticoincidence domes, while the upper detector assembly, analogue and digital electronics were provided by international partners. To calibrate the COMPTEL instrument the project scientists had to look for a high-energy gamma source and found one just 10 kilometres away at the GSF facility in Neuherberg (now Helmholtz Zentrum München). This large research centre is engaged in radiation research with its main focus on health and environmental issues. However, the Helmholtz scientists were quite excited about participating in astronomy and actually played an important role in the COMPTEL space project. The GSF accelerator provided the gamma ray source to calibrate the instrument, but a new shed had to be built to house COMPTEL, as it was too large to fit into their experiment hall.

↑ COMPTEL.

↑ Unplanned spacewalk: the main communication antenna of CGRO had to be released manually.

For EGRET, MPE was responsible for the design, construction, and testing of a pressure tank, which was made of aluminium, to contain the core of the gamma-ray telescope. This was basically a stack of spark chambers and associated trigger detectors, which were operated in an atmosphere of noble gases with more or less ambient (Earth) pressure. Individual high-energy gamma rays were detected, imaged and recorded in these spark chambers, and especially for faint astronomical sources it was important to keep the local background radiation, which was caused by ambient cosmic rays, to a minimum.

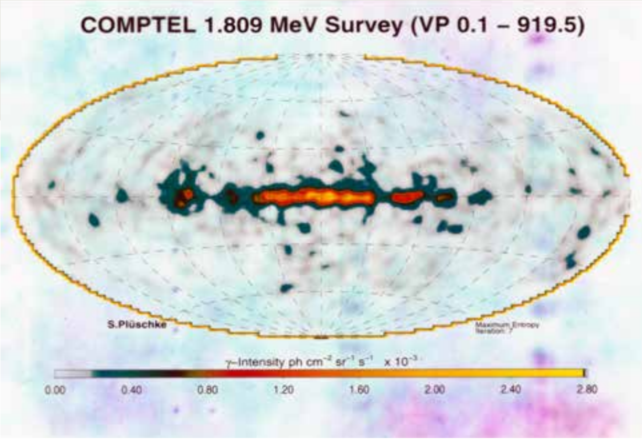
Therefore the wall of the pressure vessel had to be very thin and smooth. At the same time the pressure vessel had to withstand accidental overpressures or depressurization (in case of a leak in space) to guarantee the safety of the space shuttle. In the end, the vessel had a thickness of only 2 millimetres and was rolled over a steel form to avoid any welding seams. A plastic scintillator dome with photomultiplier light sensors was mounted on top of the pressure vessel. This so-called “anti-coincidence detector” registered incoming, charged cosmic rays and vetoed these detections in the telescope. Two more layers, a thin protection foil against visible light and a

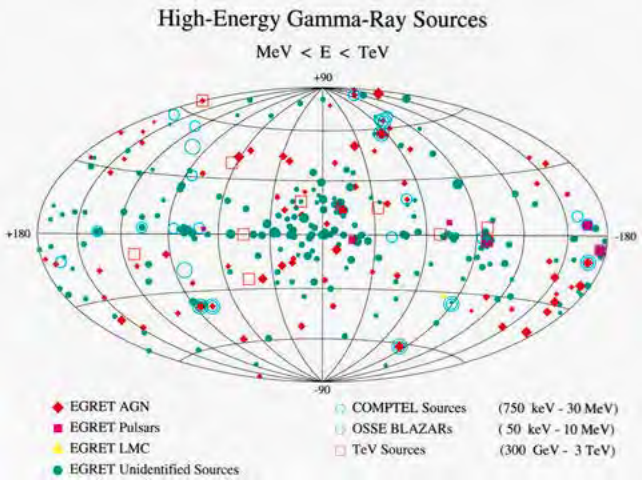
↑ The four principal investigators for the first time met three of the five shuttle astronauts who brought CGRO to orbit.

foam cover shielding the whole instrument from micro-meteorites, completed the casing.

While the pressure vessel was built in Germany (and plunged into waters of the Danube to harden the metal), the final integration of EGRET took place at the Goddard Space Flight Center, NASA, and the calibration measurements were performed on a gamma-ray beam at the Stanford Linear Accelerator, California. During the tests in 1986, the whole team experienced the shock of the Challenger disaster – and after the explosion of the shuttle a period of uncertainty about the future of the mission. The shuttle was the transport vehicle of choice and everything had been constructed to fit this launcher. In the end, the launch was only delayed rather than cancelled and the satellite was brought into orbit in 1991.

Once the observatory was above the atmosphere, the scientists experienced another shock: when the observatory was unloaded from the shuttle bay, its main antenna – needed for all future communication with the ground – did not unfold. It turned out that it was stuck and the spring





↑ The two CGRO instruments detected many previously unknown gamma-ray sources. In addition, COMPTEL produced the first-ever all-sky map in the light of a gamma-ray line (from radioactive aluminium).

was not powerful enough to release the antenna arm. One of the astronauts on-board the shuttle had to do an unplanned space walk and shake the arm loose – which then unfolded as planned.

The Compton Gamma Ray Observatory worked well for many years and produced the first complete deep survey of the universe in the light of the highest energy photons. Many new previously unknown sources were detected – about 270 by EGRET and about 40 by COMPTEL. Some sources were identified as pulsars and variable active galactic nuclei, but a large number remained unidentified. Detailed studies showed that many of these sources have their maximum luminosity in the COMPTEL energy range – it is therefore imperative to know their gamma-ray properties to understand the physics of these objects. Almost a decade later, the mission ended on 4 June 2000 with a forced re-entry of the satellite.

PEERING DEEP INTO THE UNIVERSE

↑ The HEXE balloon campaign in Palestine, Texas, in 1980.

←← The first MPE X-ray telescope “Astro 8” was launched from White Sands, USA, with an ARIES rocket in 1977.

SPEAKING LANGUAGES

Günther Hasinger

The very first MPE X-ray experiments were flown on high altitude balloons – because the atmosphere absorbs high-energy radiation, the instruments have to be brought to the upper atmosphere or above it. One of the early highlights were the first spectroscopic measurements of the magnetic field of a neutron star, a very dense and heavy stellar remnant. While working on my PhD thesis I had the opportunity to participate in two balloon campaigns, one in Texas and the other in Brazil. The physics was exciting, but also the campaign preceding it. On one occasion a Brazilian TV team interviewed me about these curious scientific balloons for a news cast. This meant that the reasoning behind the science, the aim of the balloon and how the instruments work had to be explained to a lay audience – all in Portuguese!

The strangest “misunderstanding”, however, occurred when two MPE teams went to Uberaba, a small Brazilian city, almost at the same time.

← A variation of HEXE was operated on board the Kvant module, docked to the Soviet space station Mir.

> **“Huge syringes and cups filled with Caipirinha”**

The gamma group had gone first and when the X-ray group arrived one week later, no one was there to greet them. There was only a short announcement through speakers – in Portuguese – that we should report to the information point, where we learned of a big problem: all members of the other group had fallen ill and so we were to be given some kind of vaccination right away. Proceeding to a back room, we saw huge syringes carefully arranged on a table. Wary of these instruments of torture the group unanimously declared that under no circumstances would they succumb to this treatment, and finally they were persuaded to take an oral vaccination – cups filled with caipirinha!

↑ Reimar Lüst and Joachim Trümper
with a model of the HEXE X-ray experiment.

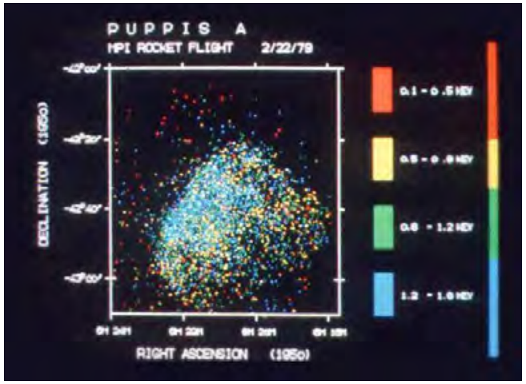
← The HEXE balloon start.

“The instrument needed to wobble artificially”

Right after these first balloon campaigns, preparations started for the ROSAT X-ray satellite mission. This involved not only hardware development but also writing some simulation software to model the observatory’s performance. One consequence of the simulations was that the instrument was so stable that it needed to “wobble” artificially in order to avoid blind spots. No one was thrilled by the idea of changing from a stable instrument to a wobbly one, but the much better eventual results justified the additional complexity. The same concept was later chosen by the US Chandra observatory.

Another issue was spotted early on in the operation of the ROSAT satellite: the altitude control system was based on four gyroscopes, with at least three being required for safe operations. Once one of them was lost, there would no longer be a safety margin. Replacement was not an option, so

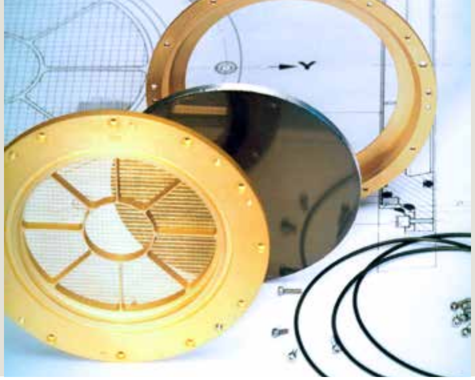
← All aspects of the ROSAT satellite mission were managed by MPE, including both hardware and software components.

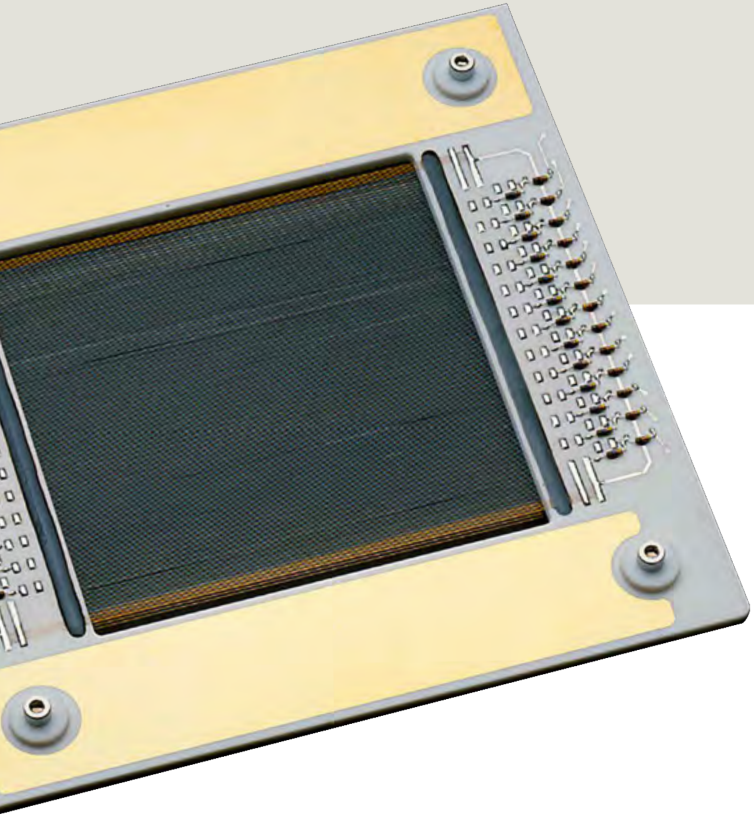


← The worldwide first X-ray colour image of a cosmic object – the supernova remnant Puppis A – was taken in 1979. This stellar explosion happened almost 4000 years ago; since then it has expanded to nearly 120 light-years in diameter.

another solution had to be found, which was implemented 1.5 years after the start – a short time before the second gyroscope indeed broke down. With the new method, the gyroscopes were replaced by measurements of the on-board magnetic field sensors, which could determine the positioning of the satellite with sufficient precision. Together with the star cameras, this assured the reliable operation of ROSAT for many years to come – ultimately several times its foreseen lifespan!

← The ASTRO-4 carried MPE's first Wolter mirror system and was launched on the Skylark rocket from Woomera in 1979.





↑ PSPC cathode grid. The incoming X-ray photons are detected by a fine wire mesh system.

WIRES AND SPARKS!

Elmar Pfeffermann

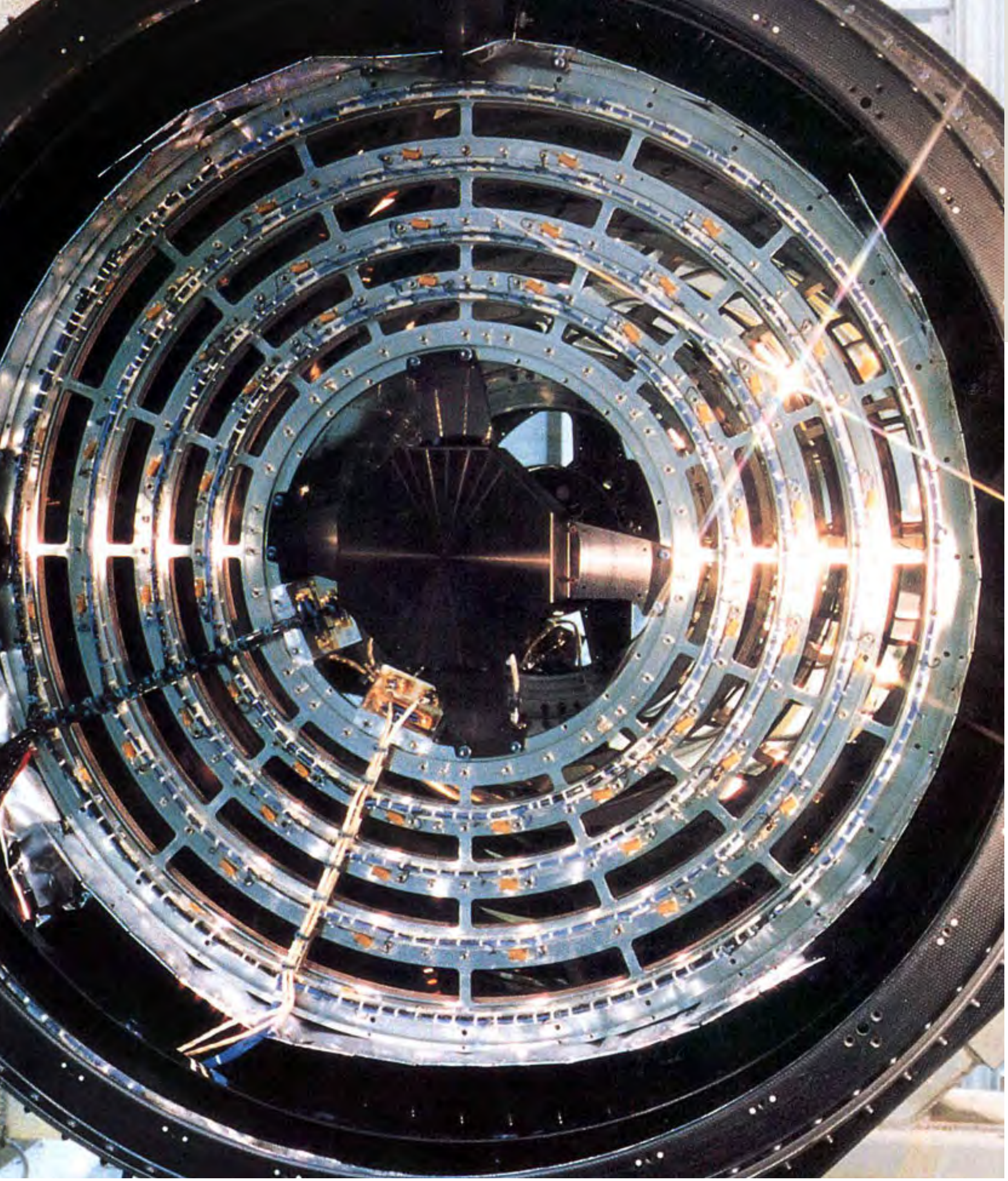
In the late 1960s MPE started to develop wire spark chambers for gamma-ray astronomy. Flown on several balloon-borne experiments and on the pioneering ESA satellite COS-B, these instruments collected important information about the highly energetic universe.

A refined version of the technology to produce wire grids was used in the late 1970s to manufacture multi-wire position sensitive proportional counters (PSPCs). These detectors were employed as cameras in the focal plane of Wolter-type-I X-ray mirrors for imaging X-ray astronomy and worked like this: incoming X-rays ionize the atoms of the gas filling, and the electrons are amplified in an electrical field. Wire grids crisscrossing the whole chamber measure energy, position and arrival time of the X-ray event. Unwanted detections of charged cosmic ray particles have to be excluded from the evaluation, thus reducing the background noise. The window, where X-rays enter the detector, is a critical component. It has to be both thin enough to allow the X-ray radiation to penetrate but also sturdy enough to withstand the pressure of the gas filling. Therefore we decided to use a foil, one thousandth of a millimetre thick, supported by a wire grid.

← The entrance window for ROSAT had to be both thin and sturdy: it had to be gas-tight but allow incoming X-rays to pass through.

↓ The focal instrumentation of ROSAT included X-ray cameras custom-built at MPE: in front one of the two PSPC's supplied with gas from the spherical tanks.

↑ The ROSAT PSPC (position sensitive proportional counter) X-ray camera with filter wheel and front-end electronics.



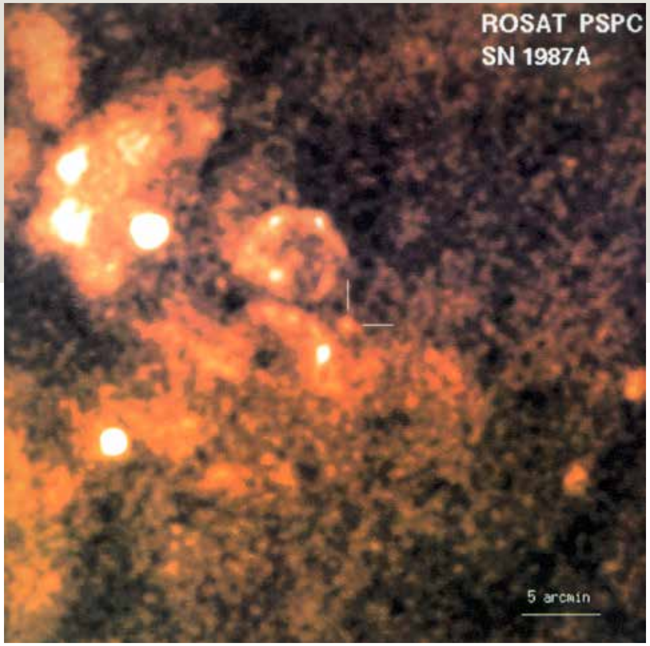
↑ Four nested parabolic-hyperbolic mirror pairs concentrated the incoming X-rays with a focal length of 2.4 metres in the ROSAT telescope. Each mirror was 50 centimetres in length and the diameter of the largest mirror was 84 centimetres.

The single X-ray events recorded by the camera are then assembled in a computer to produce an X-ray image of the cosmic source. With the energy resolution provided by the proportional counters we could produce images in four colours and our first actual X-ray image was amazing.

In 1979, the rocket payload consisting of a Wolter-type-I mirror and a multi-wire proportional counter was ready. This was launched on a rocket from Woomera, Australia, and during the useful observation time of just five minutes we collected about 5000 photons from our target, the supernova remnant Puppis-A. Already during the flight of the rocket we saw the first X-ray image in real time on an oscilloscope screen, which was calculated from the telemetry data by an 8k computer.

This experiment proved that the institute was capable of designing such missions and helped to get approval for the ROSAT mission – the "tender little plant" of X-ray astronomy would grow into a mighty oak!

→ On 23 February 1987 a star exploded in the Large Magellanic Cloud. The explosion was accompanied by the emission of hard X-rays and gamma-rays. The soft X-ray emission expected from a heated environment, however, was not seen until the middle of 1991 (indicated by the cross-hairs).



The basic principle for the ROSAT imaging camera (the PSPC) was the same as for the rocket experiments, only larger and better. The fine grids had a wire thickness of between 100 micrometres and 10 micrometres in a protective gas atmosphere, quite delicate as we found out. One of the first wire meshes for ROSAT burned up during testing, because there was actually so much energy stored in the mesh that a spark triggered by the high voltage that was applied melted the thin tungsten wires, destroying the whole device. This happened early in the developmental phase, and we modified the mesh accordingly after this accident. Even when the instrument was hit by high-energy cosmic rays during its operation in space, such an incident never happened again.

But while the main effort was spent on ROSAT, the original rocket experiments were reactivated for one last observation: the supernova explosion 1987A. Over the course of a few months, all instruments were reactivated and were flown again from Woomera – even the base had to be reopened specifically for this experiment. Our experiment was launched on 24 August 1987 and was the first and the only successful attempt to detect soft X-rays from this famous supernova remnant in its early stages. Although we found only an upper limit of the soft X-ray flux, it was an important result, which was published in Nature. A few years later, once the hot supernova explosion cloud had become much larger, the cloud could be discovered in soft X-rays using ROSAT and its PSPC with its better spectral resolution and much larger sensitivity.

> **“Although we only found an upper limit of the soft X-ray flux, it was an important result”**

↑ ROSAT was launched on 1 June 1990 from Cape Canaveral with a DELTA II rocket. With a payload of 2.5 tons, the rocket carried the biggest and most accurate X-ray telescope of that time into orbit.

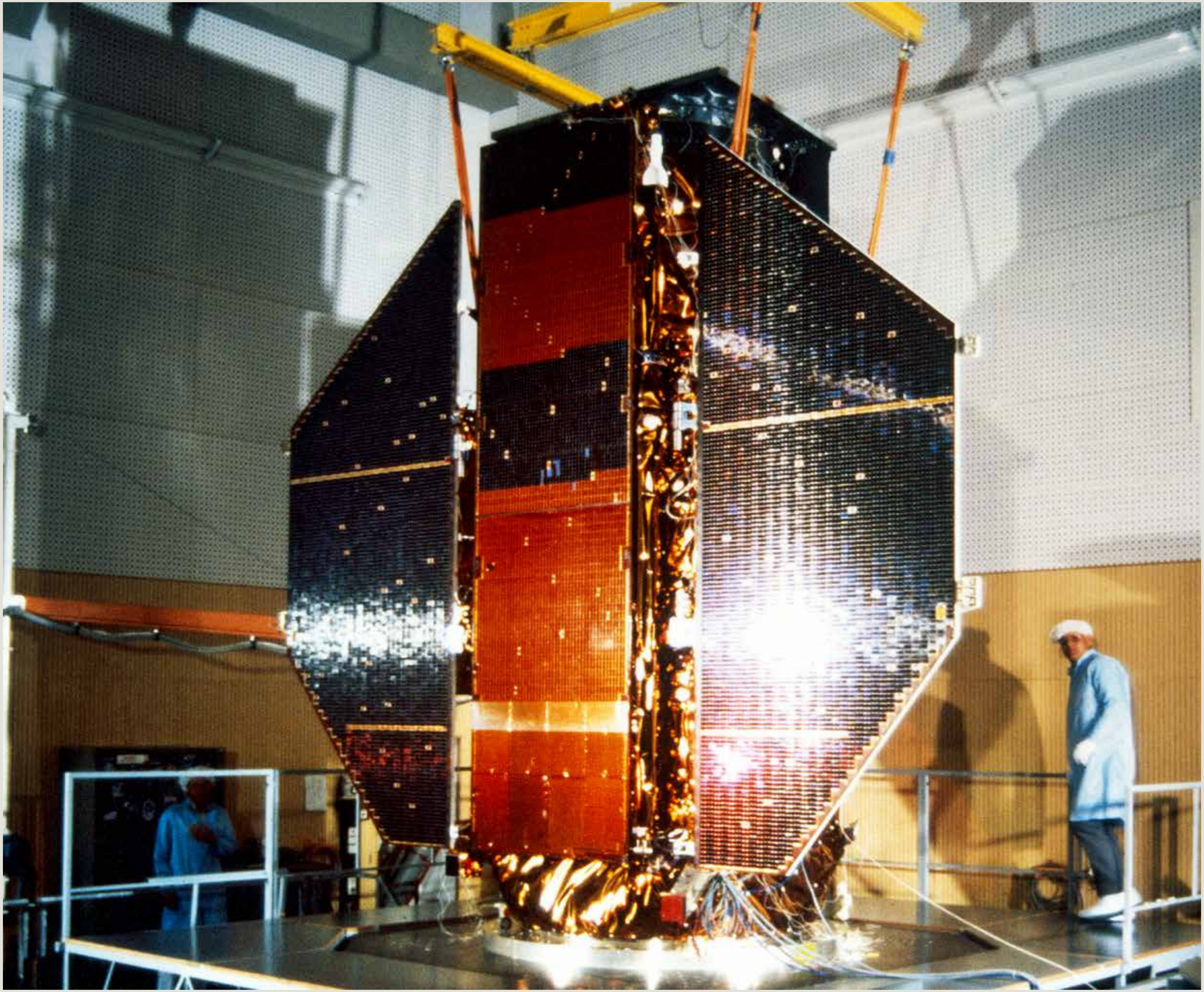
→ The ROSAT X-ray observatory after integration of all components, ready to be shipped to the launch site.

A WIDE AND DEEP LOOK AT THE X-RAY SKY

Joachim Trümper

ROSAT was the biggest project at MPE. The idea of a large X-ray telescope goes back to the early 1970s when we started a balloon programme at the University of Tübingen to study the X-ray sources discovered by the legendary Uhuru all sky survey at high energies. In 1975, we proposed a German national initiative to the Ministry of Research to build a satellite carrying a powerful X-ray imaging X-ray telescope with a hundred times better sensitivity than compared to Uhuru. We called it ROSAT and even though in later years institutions from other countries contributed both resources and instruments to the mission, the scientific lead remained at MPE, where the bulk of the instrument's hardware was constructed and tested, while the X-ray mirrors and the spacecraft were constructed by German industry.

Preparations for ROSAT were progressing rapidly when the project temporarily came to a halt after the terrible Challenger explosion. The shuttle had been selected as the carrier of choice to take the satellite into orbit, and suddenly this was no longer an option. Instead, ROSAT now needed to be slightly redesigned to fit into a rocket shroud. In particular the solar panels had to be put on hinges, so that they could be folded. Luckily, however, the



ROSAT FIRST LIGHT
16 June '90

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FIRST LIGHT

Parameters:

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fwhm_S= 144.3
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fwhm_X=   0.0
fwhm_Y=   0.0

ZOOM   =     4
linear=    10
col  0=     0
```

← The first image taken with ROSAT was of the supernova SN1987. A proud moment for the ROSAT scientists present in the control room!

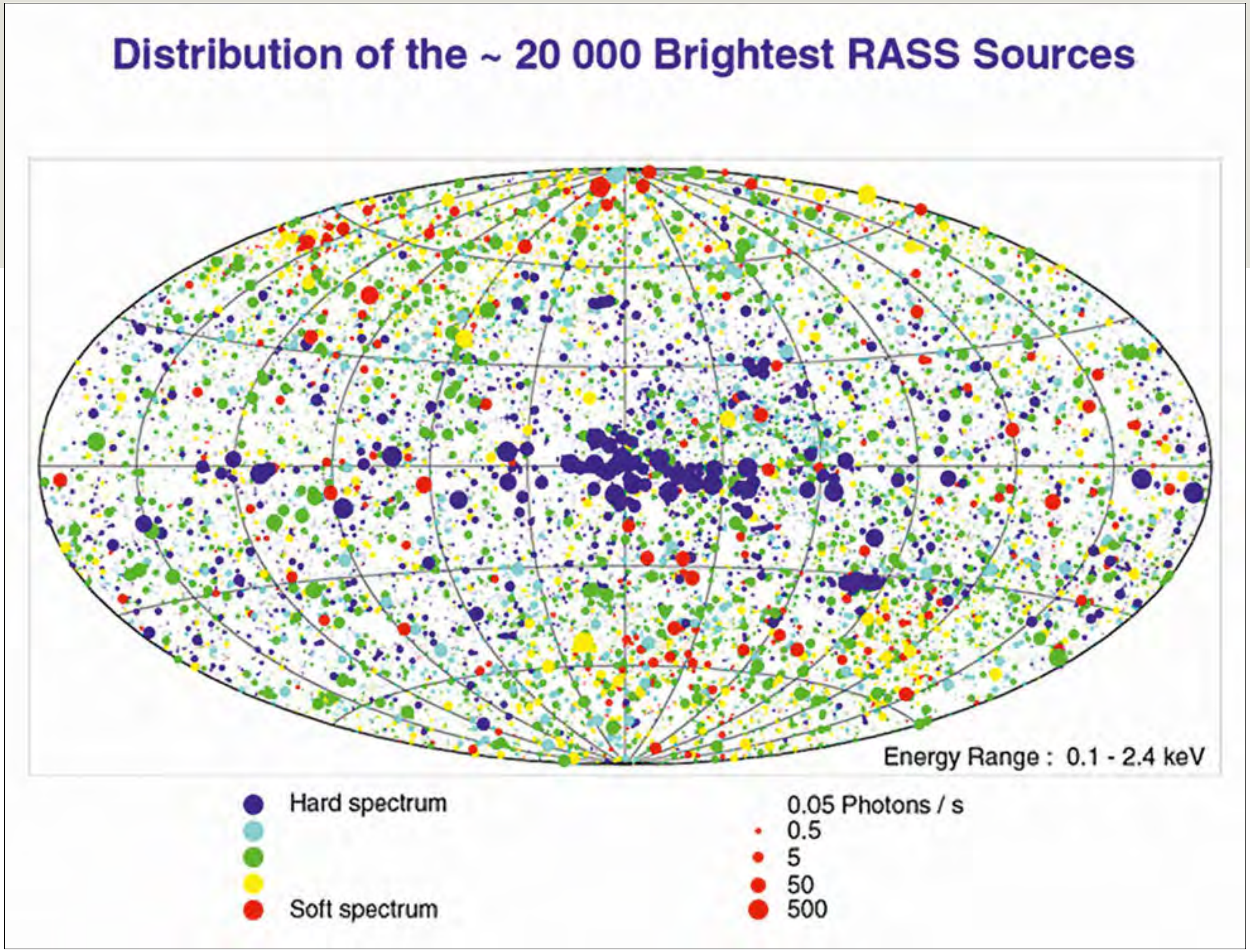
main telescope and instruments did not need to be altered and the rocket launch was indeed better for the whole observatory, which could now be brought to a higher orbit, extending its lifetime.

On 1 June 1990, ROSAT was launched from Cape Canaveral and sent its first light image to ground just two weeks later. It was exhilarating after the start and during the following weeks, when we finally saw that everything was working as expected!

During its first six months of operations, ROSAT performed the first deep X-ray all-sky survey with an imaging telescope, bringing the number of known X-ray survey sources from less than 1000 to more than 100,000. Subsequently it was used for many pointed observations over a period of eight years (instead of the planned 1.5 years), becoming the main workhorse for X-ray astronomers for the whole decade. X-ray astronomers made many, sometimes surprising discoveries with ROSAT data – and its archives are still being used today with on average two papers being published per week, 15 years after the end of the mission.

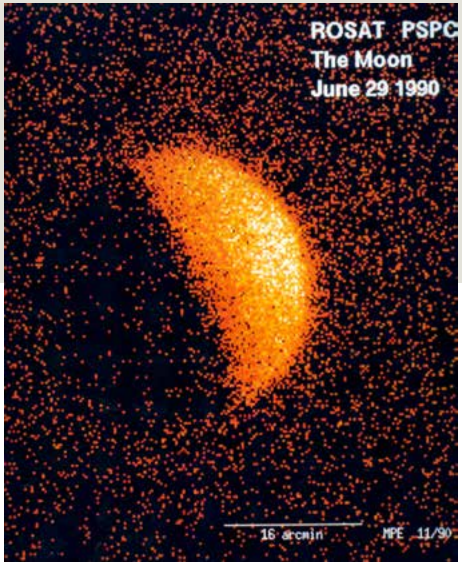
ROSAT targets ranged from nearby objects, such as the Moon or comets – these "dirty snowballs" surprisingly show up strongly in X-rays due to an interaction of solar winds with water molecules in cometary comae – to stars and stellar remnants in the Milky Way and nearby galaxies to far-away, extragalactic sources. With its much higher sensitivity and resolution

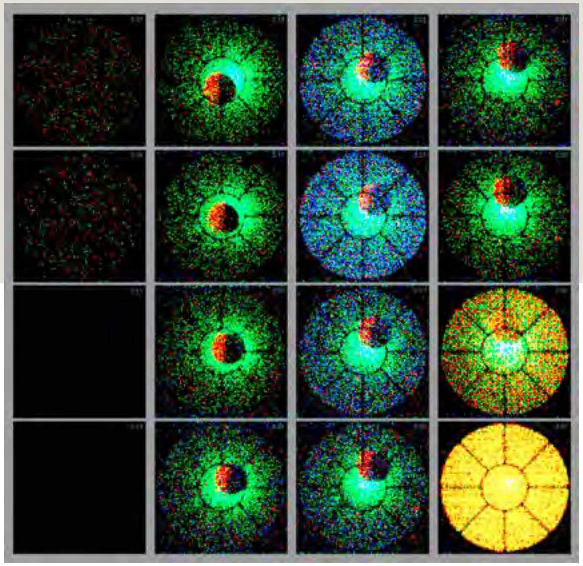
> **"ROSAT performed the first deep X-ray all-sky survey"**



← ROSAT surveyed the whole sky for the first time with an imaging X-ray telescope, yielding a total of more than 100,000 X-ray sources.

than previous instruments, ROSAT brought a wealth of discoveries: the new class of super-soft X-ray sources in the large Magellanic cloud, representing white dwarfs showing nuclear burning at their surface, the first millisecond pulsar in X-rays, neutron stars showing purely thermal emissions, the powerful jet of the active galactic nucleus NGC 1275 blowing bubbles into the intergalactic medium of the Perseus cluster, and many more. It also answered the riddle of the cosmic X-ray background, dubbed





← The occultation of Scorpius X-1 was observed by ROSAT on 20 February 1998. The waning X-ray half-moon (red) is scrolling across the scattering halo of Scorpius X-1 (green) to the top right.

↑ The first X-ray image of the Moon was taken by ROSAT on 29 June 1990: the Moon is occulting the X-ray background, but in X-rays half of the Moon appears bright from reflected solar radiation (even though the reflectivity in this wavelength range is very small). The counts on the dark side are not from some mysterious lunar radiation but are due to the solar wind interacting with gas lost by the Earth's atmosphere.

the "Holy Grail of X-ray Astronomy" by its discoverer Riccardo Giacconi. ROSAT resolved about 80% of these diffuse emissions into individual sources, mostly active galactic nuclei. Its main camera, the PSPC, was actually the first instrument that could image the X-ray background directly.

Finally, on 20 February 1998, one of the last observations with ROSAT showed the occultation of the bright X-ray source Scorpius X-1 by the Moon. This brought the observatory full circle back to the origins of cosmic X-ray astronomy, as this object was the first cosmic X-ray source discovered in 1972 along with the X-ray background – by a rocket observation scheduled to detect the lunar X-ray flux.

→ The latest PANTER extension was constructed under clean room conditions.

DEDICATED FACILITIES

← Heinrich Bräuninger (left) and Joachim Trümper (right) inspect the 130-metre-long vacuum tube.

X-RAY MISSIONS BRAVE THE PANTER

Heinrich Bräuninger, Vadim Burwitz

X-ray astronomy started to pick up speed in the 1970s. As this was a completely new field for astronomical research, instruments and telescopes had to be built based on first principles. Initially the X-ray group was hosted by the University of Tübingen, where the team prepared rocket experiments to study solar X-ray radiation. The small test facility there provided first experience with testing and calibrating the scattering of X-rays on mirror surfaces, demonstrating that for successful experiments a proper test facility is absolutely essential.

> “Smoothest mirror surface worldwide”

↓ Flowers for the physicists? The ROSAT mirrors were transported in a temperature-controlled delivery truck of a local gardener to minimize the thermal stress on the regular transfers between the Zeiss manufacturing site in Oberkochen and the testing facility in Neuried.

After moving to Garching, the ZETA test facility was built which had a 10-metre vacuum tube. At that time, the main focus was on searching for suitable materials for X-ray mirrors and polishing their surfaces. The very low level of micro-roughness even earned the institute an entry in The Guinness Book of World Records for the “smoothest mirror surface worldwide”.

→ In January 1980, the beam pipe was evacuated for the first time and imploded as the pressure fell below 100 mbar. Small deviations from an ideally circular profile combined with increasing vibrations caused the tube to implode, damaging the wall of the barracks housing the vacuum pumps. The second vacuum tube therefore has reinforcement rings.

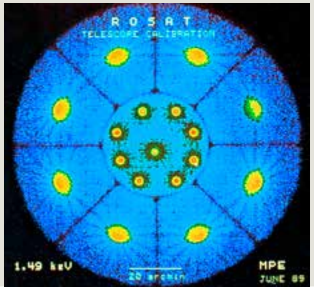
For developing and building larger X-ray mirrors, however, it became necessary to build a test facility with a longer baseline. In Garching, a suitable area could not be found – not even with some clever surveying – and so the team had to look elsewhere. Finally, the first PANTER facility was built on the premises of an industrial partner, Pantolsky, in Neuried, who provided MPE with vacuum tanks.

The first test facility had a length of 30 metres but was soon extended to 130 metres, as the projects became bigger as well – a growing test facility adapted to the task at hand. In 2012, the PANTER facility was enlarged by a further 13 metres to be ready for future projects with a larger diameter and a longer focal length.

At one end the beam starts from a small tank containing the X-ray source and goes through the beam tube all the way to the main test chamber enclosing the telescope that is to be studied. Because X-rays would be absorbed by air molecules, the whole PANTER needs to contain a vacuum. This actually resulted in an accident while the facility was being evacuated

“What a shock!”

→ From the calibration tests of ROSAT mirrors: images of point sources that are off-axis with respect to telescope optics appear spread out rather than point-like.



↑ At CERN, the CAST experiment aims to detect axions, a special type of elementary particle that should be produced inside the Sun. The signal-to-noise measurements use an ABRIXAS mirror and a pn-CCD camera developed at HLL.

↑ The PANTER test facility in Neuried. The 130-metre-long vacuum tube is visible at the lower edge of the industrial area; the actual laboratory is housed in the building on the left.

for the first time, leading to an implosion of the beam pipe along all of its 130 metres. The design error, however, was quickly remedied and PANTER was officially inaugurated in October 1980.

A long baseline between the source and the detector is needed so that the X-rays are quasi-parallel when they reach the mirror surface, mimicking astronomical radiation from sources that are very far away. The profile of X-ray mirrors can then be measured with a very high degree of accuracy.

Originally PANTER was built mainly to support the ROSAT telescope development. The telescope was designed with eight mirror shells (with an additional two for verification purposes)

← With the latest extension, PANTER is ready to test the next generation of X-ray missions.

↑ The vacuum chamber connected to the extension of the beam pipe.

and each of these shells had to be transported back and forth between the Zeiss manufacturing site and the test facility six to eight times. For this project, the institute was not merely contractor for the mirrors, but was responsible for the entire planning and testing phase. The results achieved by the test facility as well as the interpretation of the Zeiss profile measurements were actually of such high quality, that a Zeiss technician once commented that MPE now knows more about their manufacturing facility than they did themselves. From May 1989 to February 1990, the ROSAT X-ray mirrors and its Wide Field Camera successfully passed their final tests and calibrations. ROSAT was launched a few months later, in June 1990.

In the past decades, the PANTER test facility was involved in nearly all major X-ray astronomy missions. For most of these projects, the object of study was telescope optics, but cameras and detectors as well as filters have also been tested and calibrated. Currently seven X-ray mirror modules, with 54 nested mirrors each, are being tested and calibrated for the eROSITA project, which will be launched in 2014 – and PANTER is ready to sink its teeth into whatever new tasks future X-ray missions might bring.

↑ Up to 800 process steps are necessary for the production of the high-end CCDs developed at HLL, such as photolithography, deposition of dielectrics or ion implantation.

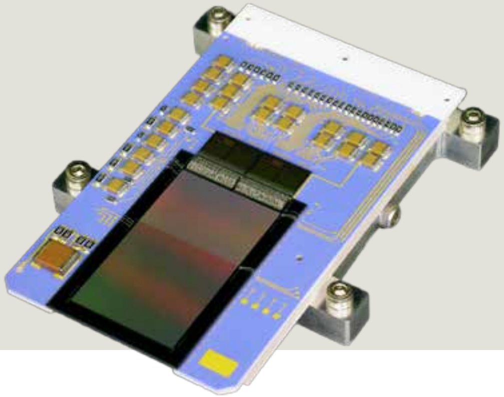
HIGH-END CHIPS MADE TO ORDER

Lothar Strüder

> “The world’s largest direct converting X-ray CCD”

Designs and developments for the ROSAT mission were well under way when MPE, and in particular its director Joachim Trümper, took the decision to establish a semiconductor laboratory, together with the Max Planck Institute for Physics (MPP) and its director Hans-Peter Dürr. It had become clear that for cutting-edge research in high-energy physics and astronomy, high-performance silicon detectors were needed, which were not commercially available at that time – and industry was not interested in doing research and development for such a small market.

After several intermediate steps and intense negotiations, a contract was signed between MPE and MPP in 1990, and the Halbleiterlabor (HLL) moved to the former premises of the Fraunhofer-Institut für Festkörpertechnologie in Munich, where they also rented a 250 m² cleanroom to manufacture high-end silicon sensors. These were needed especially for the XMM-Newton satellite project, which demanded a challenging large X-ray imager. Over the next years, HLL successfully realized the

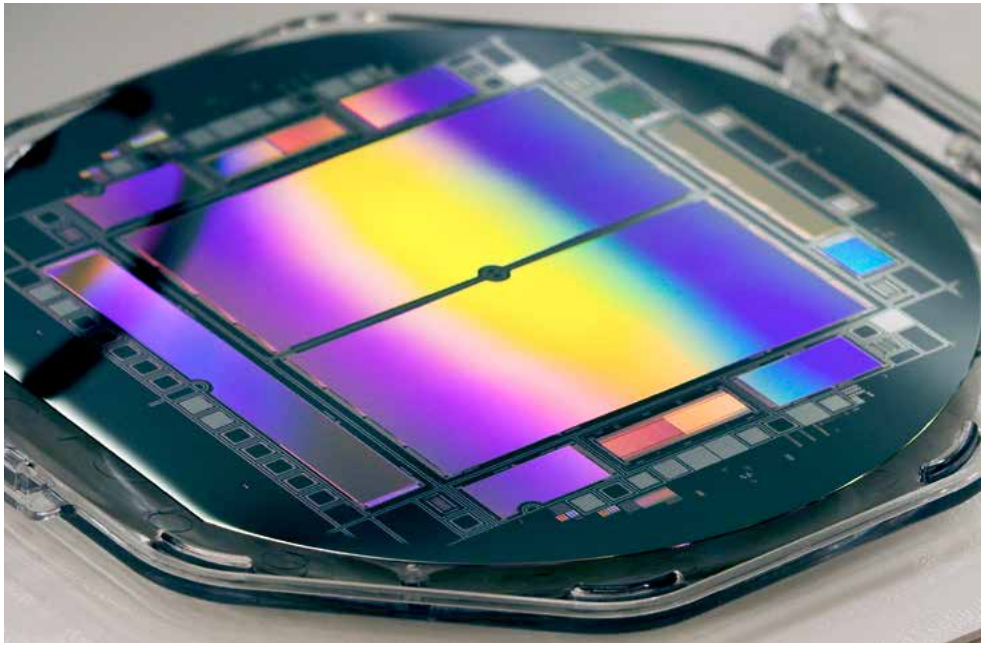


→ Prototype of the eROSITA pnCCD detector module.

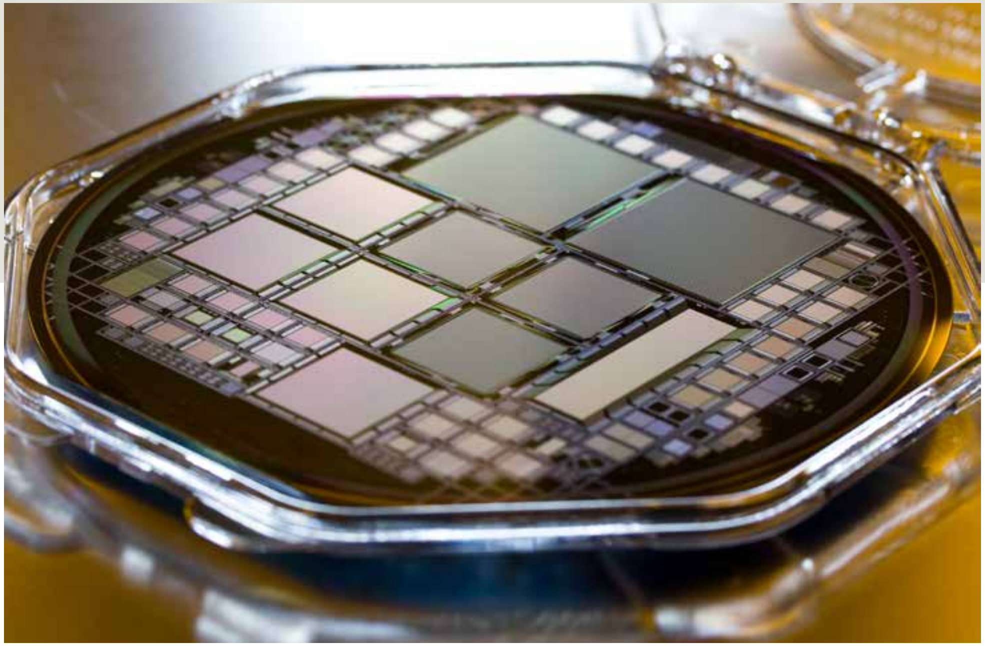
implementation of a 36 cm² pnCCD for XMM – at that time the world's largest direct converting X-ray CCD.

At the end of the 1990s, HLL needed to find a new home, as their laboratories no longer conformed to regulations. Due to good contacts between the Max Planck Society and Siemens, HLL found a new location at Siemens' research campus in Neuperlach, with their main research and production facility in Hall 72. There they not only designed and manufactured chips for next generation projects in high-energy physics and astronomy, they also started to think about how to transfer their research and surplus production to society at large.

And so in 2002, a non-profit company PNSensor was founded to contribute to the developments at HLL, to support the operation of the cleanrooms and to work out a concept on how to commercialize silicon detectors originally developed for scientific experiments. Such silicon drift detectors and pnCCDs are nowadays used in many industrial applications, ranging from quality



→ This pnCCD for the Centre for Free-Electron Laser Science is larger than the eROSITA detector but based on the same basic design.

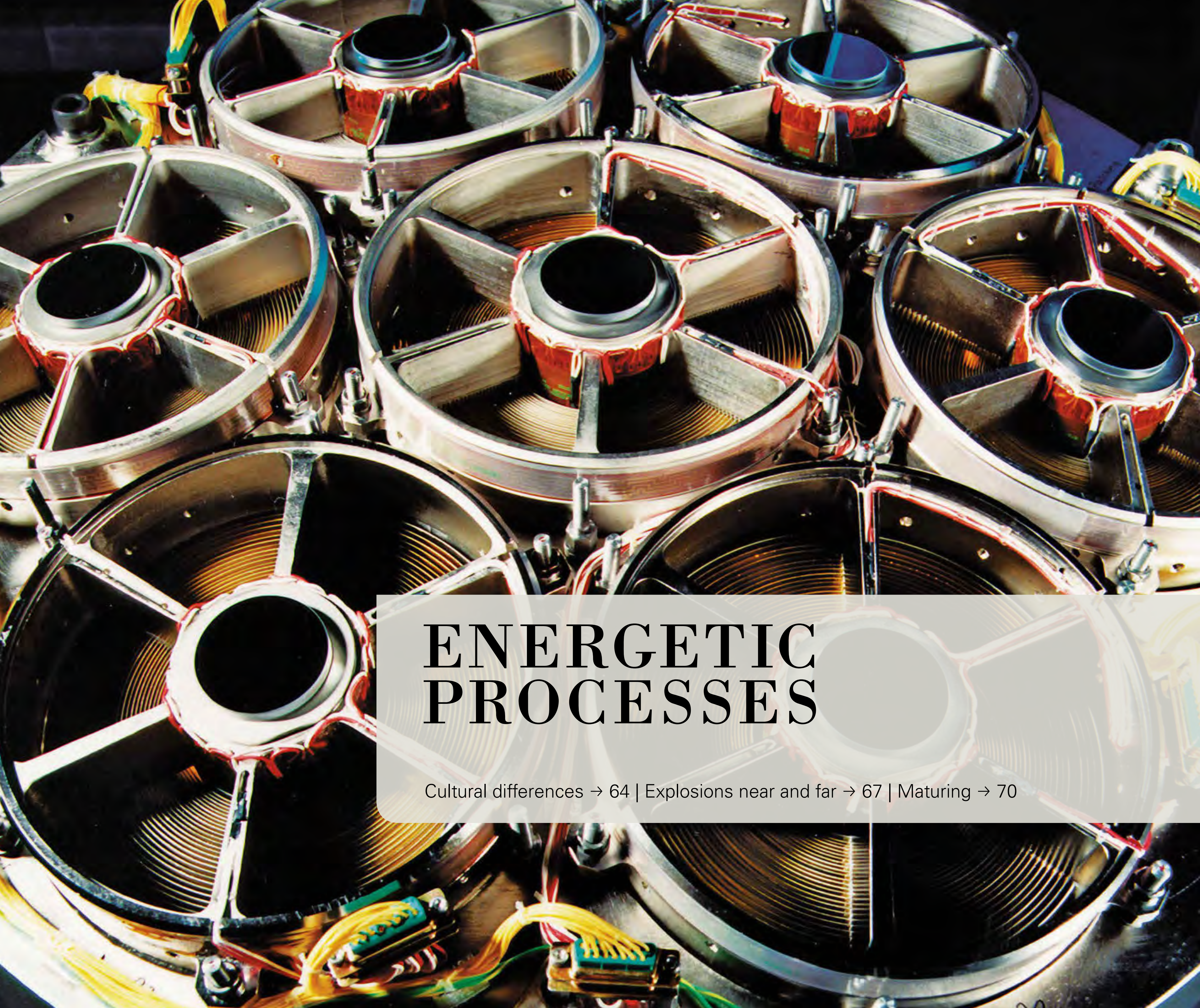


← The X-ray detector for the next generation of X-ray telescopes, based on the concept of active pixel sensors, is already under development. It includes 10 times more pixels.

assurance to X-ray fluorescence and material analysis. There they are used to analyse works of art, for studies in forensics or aeronautics, and to verify the authenticity of jewellery, to mention just a few examples.

The cooperation between the different groups from MPP, MPE and PNSensor worked beautifully, everybody wanted to contribute to the success of this enterprise. Quite often people were "on loan": from MPP for the XMM-Newton project and to MPP for the CERN experiment ATLAS or later the Belle II particle physics experiment in Japan. And while HLL was set up explicitly to serve the needs of the two institutes, occasionally they would also help out when other Max Planck institutes needed something in a hurry, such as for the CERES experiments at CERN or the SOHO mission. For the latter, the astronomers urgently needed some sensors, as the previous three years of development had not yielded the expected results. In the end the wafers were processed "hot from the oven" and installed on the satellite after a minimum of tests – and they are still working, 18 years later!

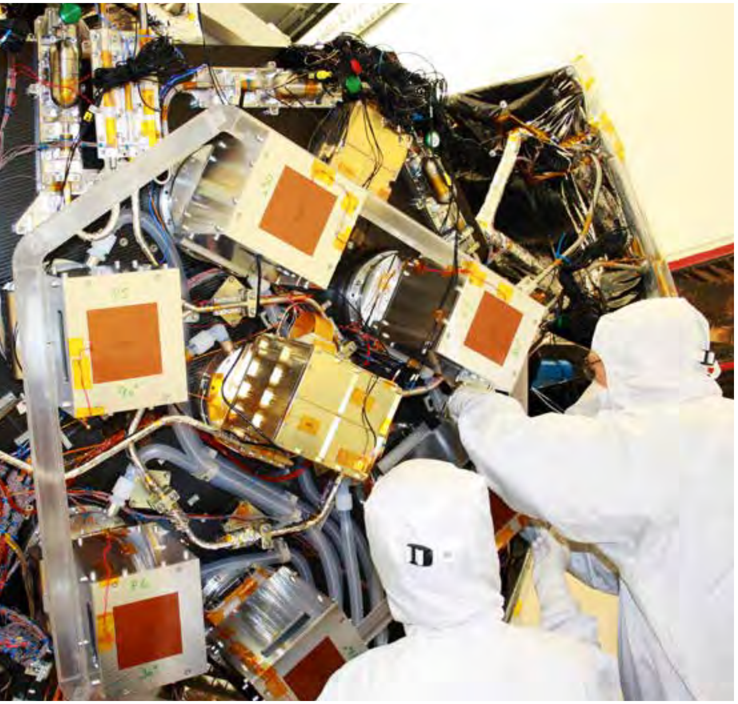
→ The eROSITA design is to a large degree based on the small German ABRIXAS satellite.



ENERGETIC PROCESSES

← The space mission Spectrum-Röntgen-Gamma will be launched with a Zenith-2SB/Fregat rocket from the Russian launch site Baikonur in Kazakhstan and brought to its orbit at the so-called L2 point, some 1.5 million kilometres from Earth.

↓ Highly sensitive X-ray CCD cameras are in the focal point of each mirror module, where they have to be cooled to -90°C.

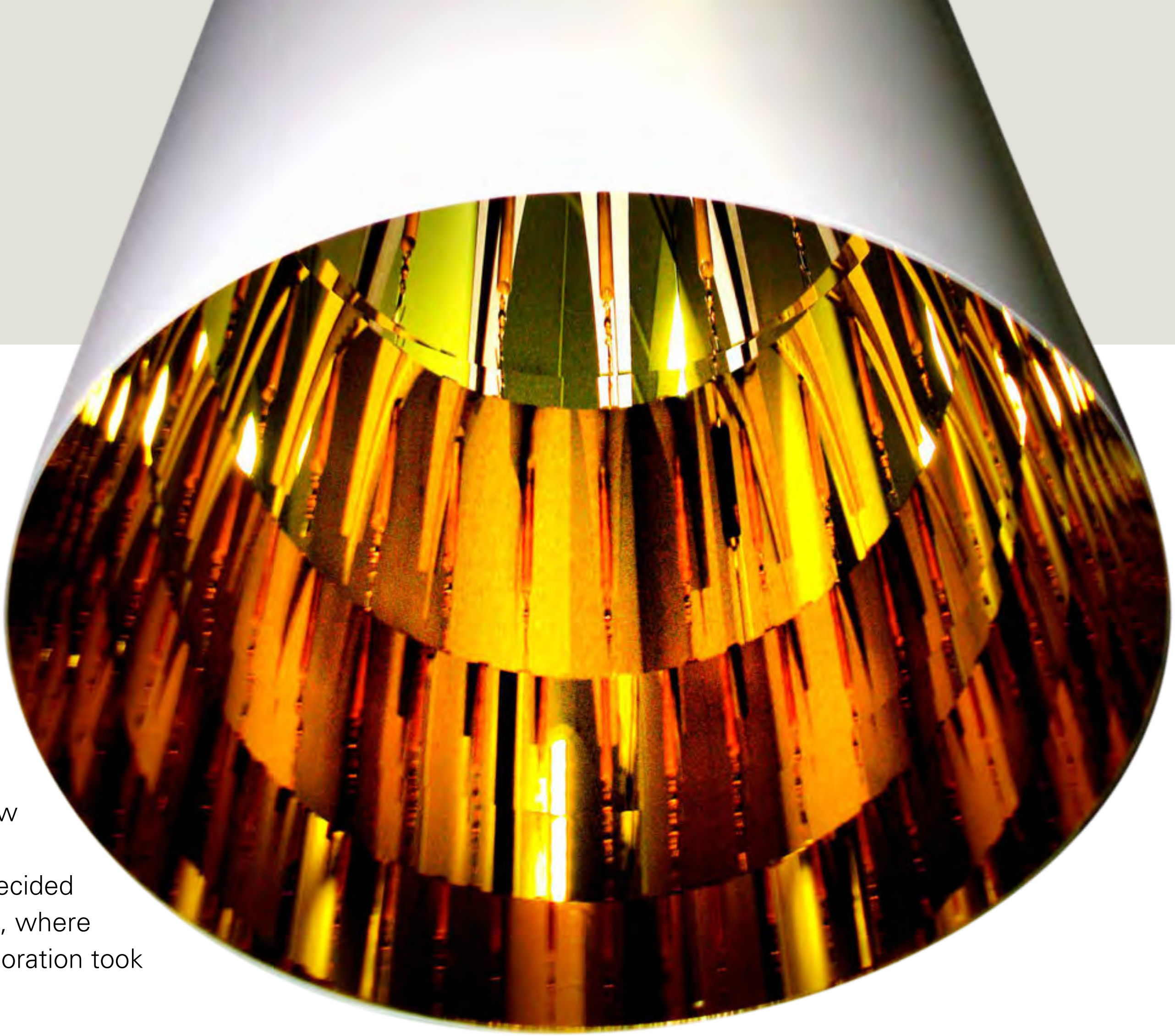


CULTURAL DIFFERENCES

Peter Predehl

The new millennium dawned with a new discovery: there seems to be a mysterious force pushing the universe faster and faster apart: dark energy. Its effect can most readily be seen on the largest scales, and it is very important to gauge its influence over cosmic time, which gave new impulse to an idea that had been discussed in various forms over the past years: an X-ray telescope to study the distribution of galaxy clusters in the universe. By comparing these observations with cosmological models, the eROSITA project will be able to determine the parameters of dark energy with high enough precision to distinguish between different theoretical models.

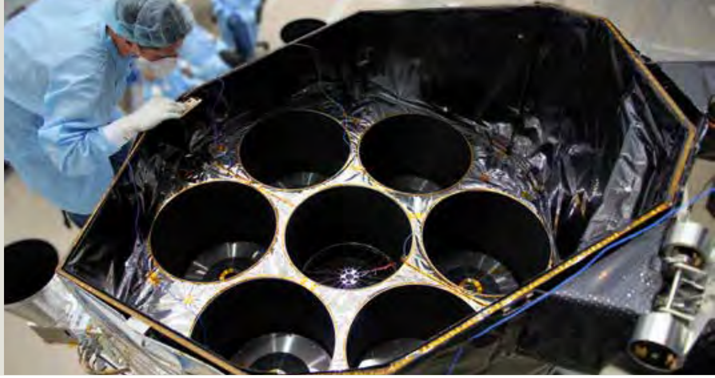
eROSITA's mirror system is based on previous developments at MPE, reaching back to the small German satellite ABRIXAS. This was originally designed to extend the ROSAT mission to higher energies, but unfortunately once in orbit the batteries did not work as expected and the satellite was lost. The next idea was to put basically the same system on



the ISS – the project was called ROSITA – but it turned out that neither the shuttle as transport vehicle nor the ISS as host were suitable for such an X-ray mission. But once the idea to study dark energy had come up, it also became clear that the telescope had to be larger than what was planned until then – the basic design of the new "extended ROSITA" or eROSITA (with seven larger mirrors) was decided on in a three hour flight to Russia, where the first talks for the future collaboration took place.

Collaborating with the Russians took some getting used to – not only because bureaucracy and customs regulations were quite complex and time-consuming. Whereas prevalent stereotypes were not fulfilled – there was a bottle of vodka on the table for each meeting but none was drunk – the Russians work in a completely different way. Great emphasis is put on formalism and procedures: agreeing on the minutes of the meeting sometimes took longer than the meeting itself. And while it is very unusual

↑ The eROSITA telescope consists of seven modules with 54 nested mirrors, which have to be extremely smooth.



→ With a set of seven telescope modules, eROSITA will provide the most accurate all-sky view in X-rays.

↑ The quality of the eROSITA mirrors as well as that of the cameras, electrical and cooling systems was verified in a complex test series.

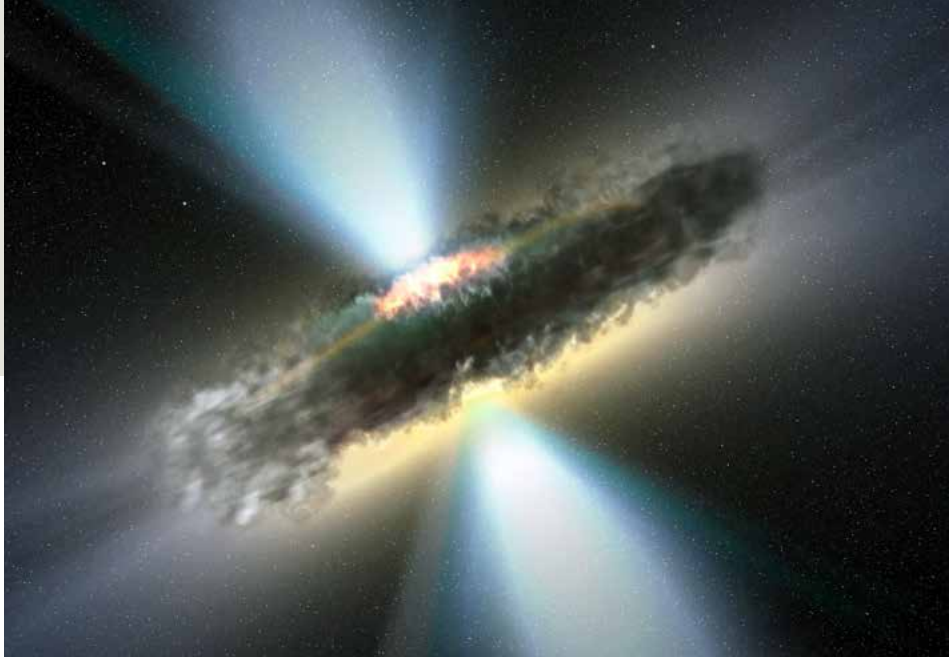
↑↑ The transportation of eROSITA mirror components from Italy to Garching in a VW bus.

to get a response to a question right away, it pays off to be patient: the Russian colleagues then think very carefully about everything and search for solutions, often coming up with very pragmatic answers.

Manufacturing the seven telescope modules, consisting of 54 nested special mirrors each, posed a major challenge. They were produced in an international collaboration, which involved many trips over the Alps. When the first mirror was transported in a VW bus from Italy to Garching, with each bump in the road the team discussed how much stress the mirror could withstand – the bumps being accompanied by a rattling sound in the back. On arrival it turned out that this noise was due to a pair of pliers left on top of a metal box, the mirror was safe and sound!

The integration and testing of eROSITA is being carried out at MPE, which is quite unusual for such a large project. And while there were some minor glitches and delays, the main qualification tests were well within specifications. With launch scheduled for 2014, eROSITA will be the main instrument on the Russian space mission Spectrum-Röntgen-Gamma. Its observation of about 100,000 galaxy clusters will make the eROSITA sky survey about 30 times deeper – peering much farther back into the early universe – than the very successful ROSAT mission.

→ Every galaxy probably harbours a supermassive black hole at its centre. As they feed on matter from their surroundings, superheated gas streams away in jets, emitting very high energy radiation.



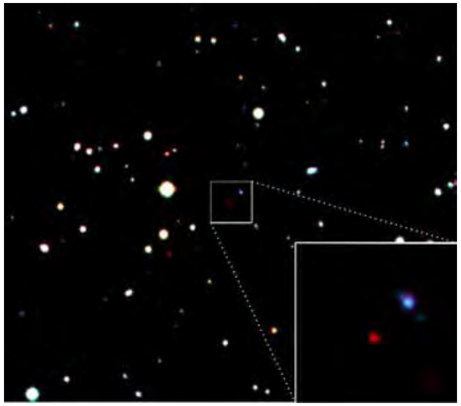
EXPLOSIONS NEAR AND FAR

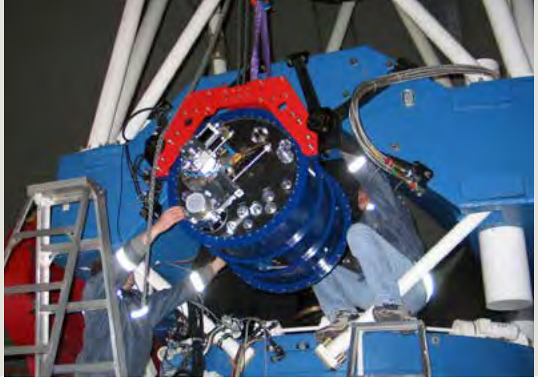
Roland Diehl / Andreas von Kienlin / Jochen Greiner

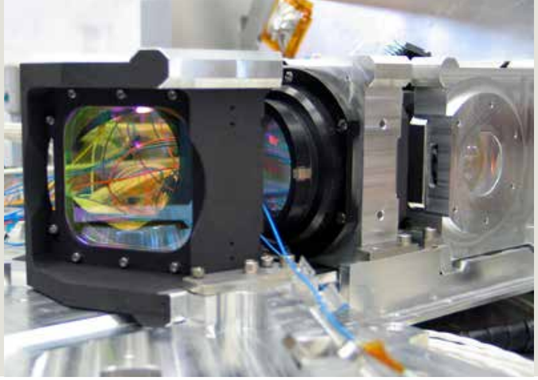
The high-energy satellite observatories of the 1990s had found a lot of transient sources, i.e. sources that change their intensity over time. Some of them shine up to 100,000 times brighter than before and then fade over the course of several days or weeks. The most energetic of them can be seen up to vast cosmic distances, but nearby explosions also left their traces in the interstellar medium of our own galaxy that can still be observed today.

Even from orbit, however, observing at the highest energies is a difficult task. Because this radiation is several million times more energetic than visible light, it passes right through most matter with hardly any interactions. For the anticoincidence shield of the SPI instrument for the "International Gamma-ray Astrophysics Laboratory", the MPE team therefore relied on dense bismuth germanate oxide crystals, extending around the bottom and the side of the detector. Each of the 91 crystals was fitted

↓ In 2009, GROND broke the record for the most distant object in the universe: it observed a gamma ray burst with a redshift of about 8, which means that its light was emitted when the universe was only about 600,000 years old.







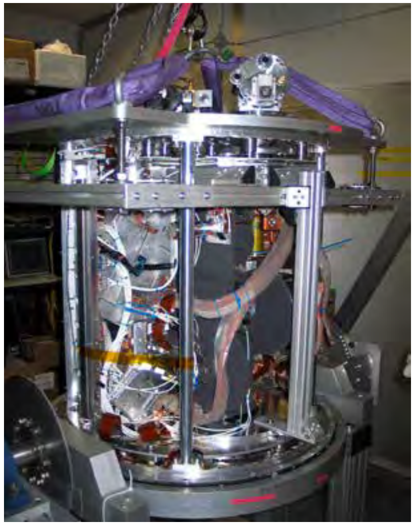
← Because the camera simultaneously observes in the optical and the infrared wavebands, intricate optics are required.

↑ The main requirement for the telescope hosting GROND was that there should be an 8-metre-class telescope close-by for spectroscopic follow-up observations once an interesting burst was found. In spring 2007, GROND was therefore installed at the 2.2 metre MPG telescope operated by the European Southern Observatory in La Silla (Chile), not far from ESO's Very Large Telescope.

with two photomultipliers – all individually tested – to detect light flashes triggered by incoming gamma rays. And while the anticoincidence shield nominally has the task to veto the observation of flashes that are too energetic, by its very design it actually led to the detection of several gamma ray bursts and other giant flashes.

INTEGRAL has provided us with a wealth of data on the highest-energy processes in the universe: Some of the elements produced in stellar explosions are radioactive, and their gamma-ray radiation traces the ejecta of such explosions as they enrich the universe with elements heavier than hydrogen and helium. Even characteristic gamma-rays from anti-matter can be observed: this is produced when these positrons collide with electrons, their anti-particles; both particles disappear and transform into radiation. INTEGRAL showed us that vast quantities of positrons annihilate in the central regions of our galaxy, rather than in the galactic disk where the positrons are expected to be produced.

Searching for distant gamma-ray bursts in space, actually led to the parallel development of a ground-based instrument. Once alerted that a gamma

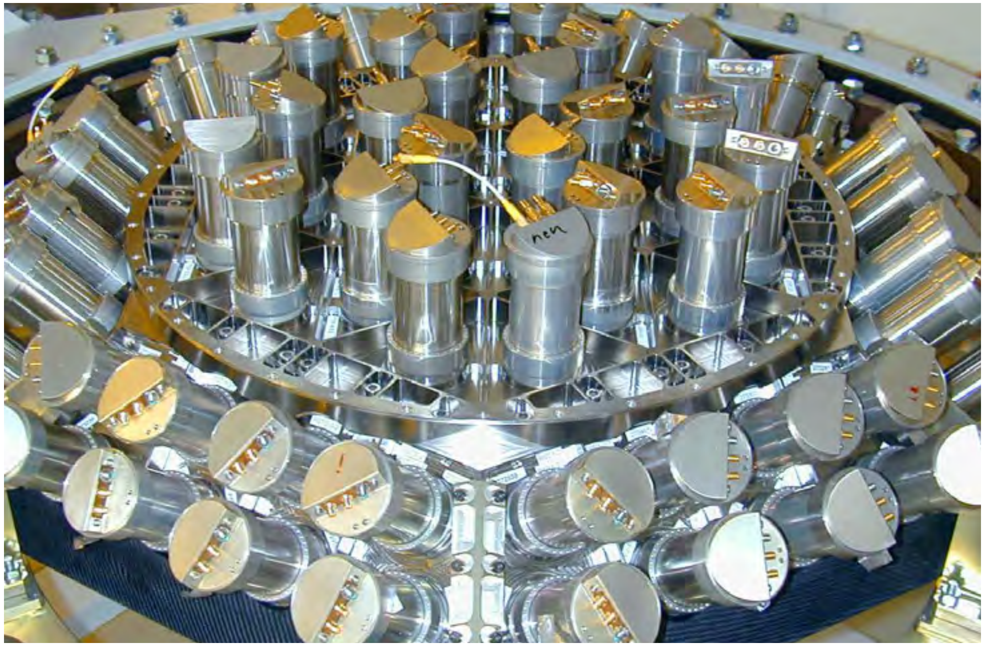


← The electric cooling for GROND also improves the vacuum: as gas particles freeze at the coldest spot, the vacuum is kept at acceptable levels throughout the whole operational period. The pump is thus only needed during routine maintenance once a year.

→ The overland trip to the INTEGRAL launch site in Baikonur in 2002 provided interesting experiences, very different from the typically well-controlled astronomic environment. Especially the entry to the rocket facility proved quite difficult, as the scientists did not come by the "approved" airplane route.

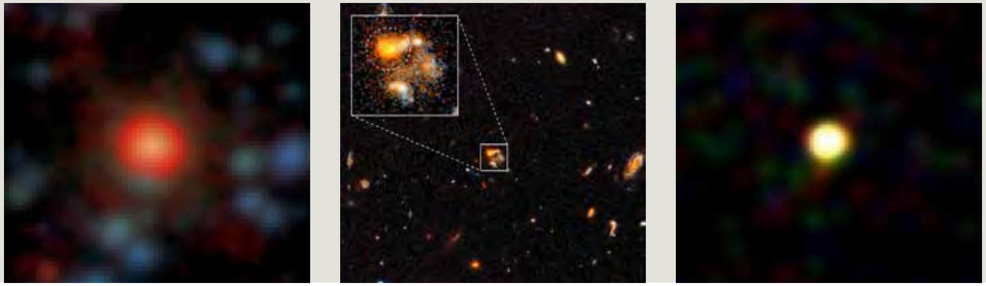
ray burst had occurred, the scientists very quickly wanted to find out whether it originated from a far-away source. The proposed method for GROND was based on the source's colour: more distant sources appear redder as their light is shifted to ever longer wavelengths. When observing in different, suitably chosen colour bands, close sources should show up in all of the images, while distant sources would appear only in the redder bands.

However, from first light in April 2007 it took more than a year until the instrument found its first distant burst. The scientists had become quite anxious, even though they did not doubt their instrument. It was unclear how frequently high-redshift bursts occurred, but were they really that rare? Indeed they are: there are about ten times fewer than predicted by theory.



→ Even though the BGO crystals around the instruments were designed to contribute to its structural integrity, SPI is extremely heavy, with a mass of 1300 kilograms.

→ These views show a "mini-quasar" being created some 8 billion years ago. The infrared and optical images show galaxy fragments and hot dust (left, centre). The X-rays (right) are being emitted by a tiny but fiercely bright disk of million-degree hot gas heated by falling in close to a massive central black hole.



↑ Three generations of high-energy directors at MPE: Joachim Trümper, Günther Hasinger and Kirpal Nandra.

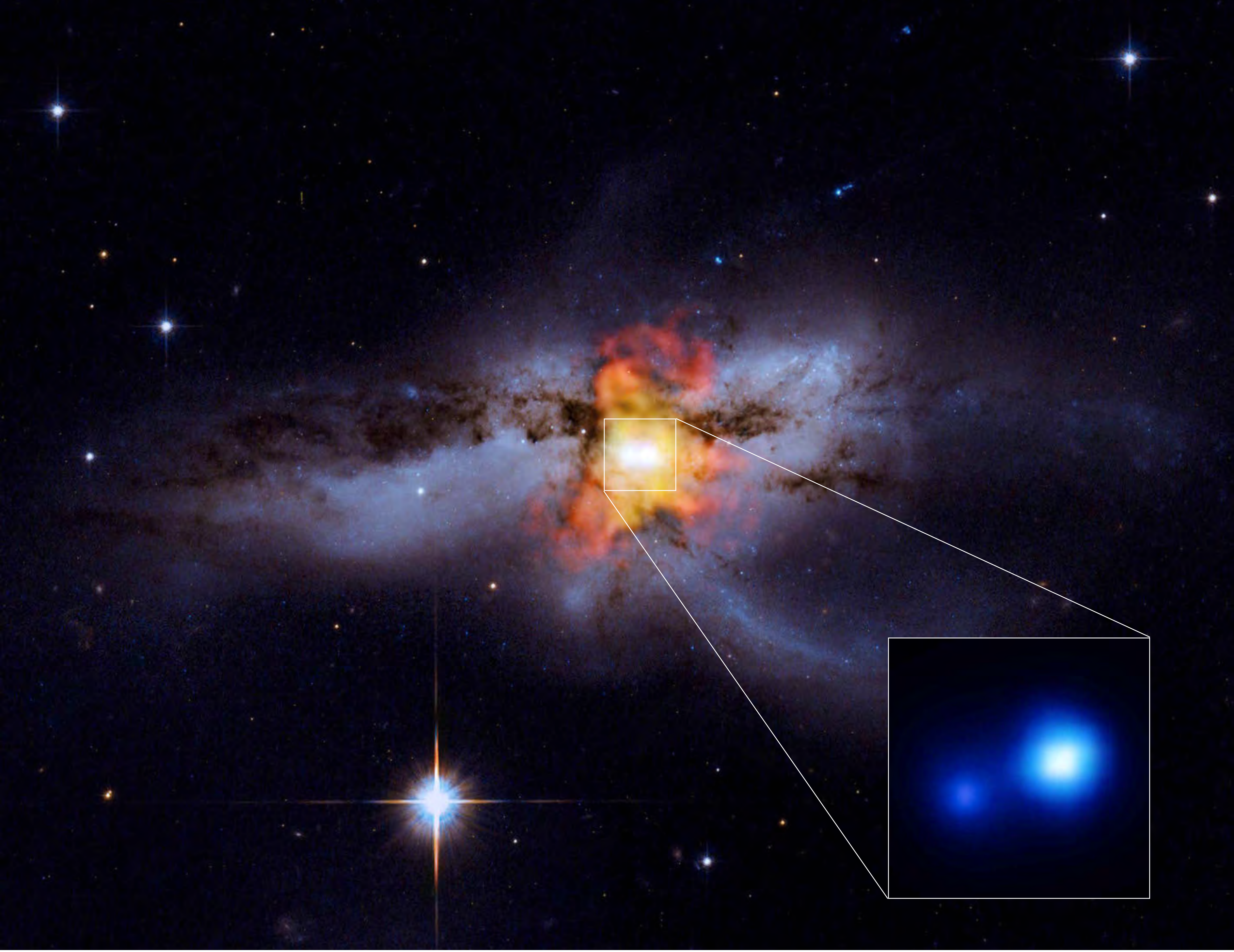
MATURING

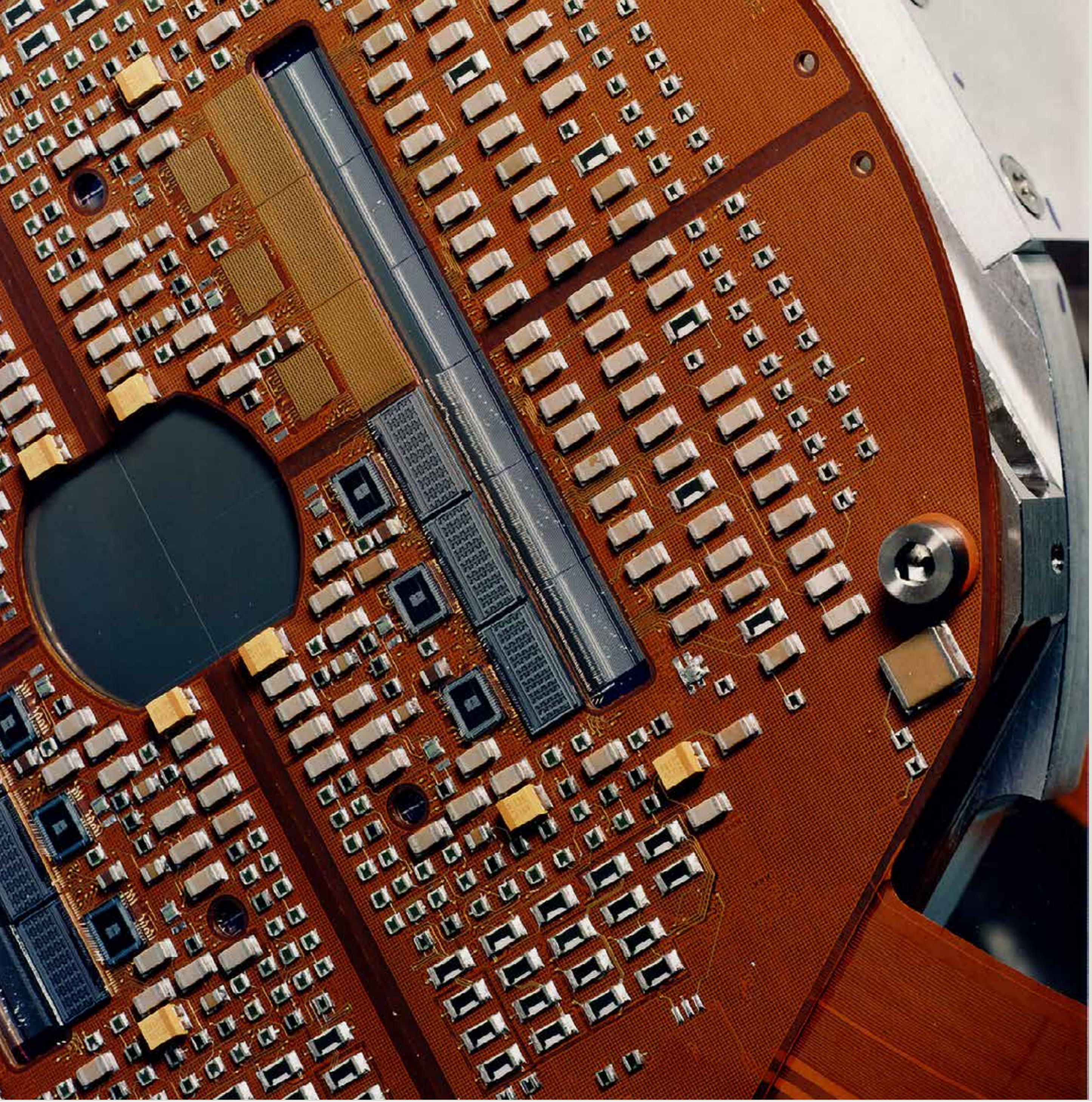
Kirpal Nandra

In 2013, X-ray astronomy celebrated its 50th year. In 2013, it is also MPE's 50th anniversary. And my own? Let's just say that's coming soon. The first two, at least, have surely now earned the right to call themselves mature.

Fifty years ago, black holes were the stuff of science fiction. Today, we can find a hundred before breakfast (of weißwurst and beer, naturally). Yet I can still vividly remember the day when I saw the first true "colour" picture of the X-ray sky, from ROSAT, shown by my predecessor Günther Hasinger at a conference around 1990. The subject has come on a long way since that moment of wonder, but the wonders have not ceased, and we still have much to learn about the high-energy universe.

→ The Chandra image of NGC 6240, a butterfly-shaped galaxy that is the product of the collision of two smaller galaxies, revealed that the central region of the galaxy (inset) contains not one, but two active giant black holes. The large image contains X-ray data from Chandra (shown in red, orange, and yellow) that has been combined with an optical image from the Hubble Space Telescope.

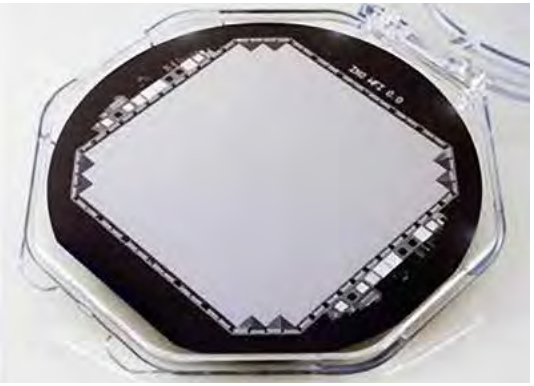




← Both ABRIXAS and XMM-Newton carried X-ray CCDs developed and produced by the Halbleiterlabor. This picture shows the electronics for power supply and readout of the twelve CCDs of the pn-camera.

↑ The Low-Energy Transmission Grating for Chandra was designed, tested, and assembled at MPE. More than 500 single grating facets with 1000 lines/mm are mounted on a ring-shaped frame with very high precision.

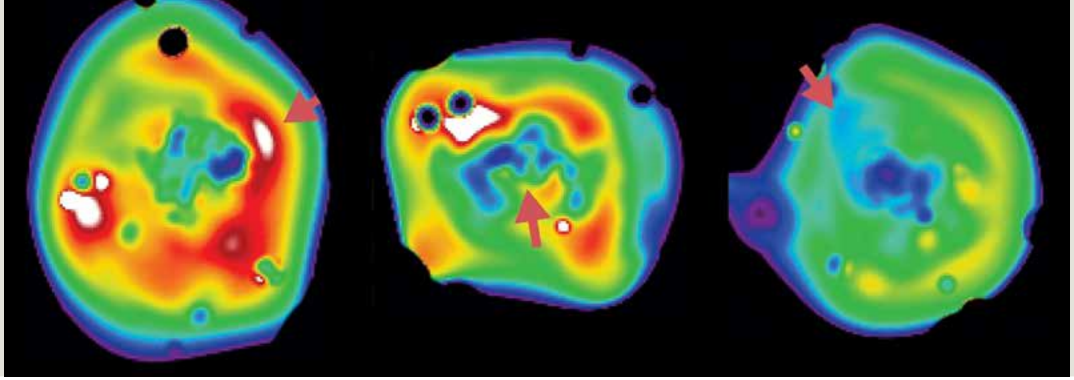
Since ROSAT, MPE has continued to push the boundaries, with major hardware contributions to the two "big beasts" of modern X-ray astronomy: XMM-Newton and Chandra. These observatories have opened up the X-ray universe to astronomers of all stripes, even if X-rays are not their main interest. With XMM-Newton and Chandra we have seen the makeup of the high energy sky in exquisite detail, whether it is light being distorted around the event horizon of black holes or huge clusters of galaxies smashing into one another. eROSITA will be the next big step, performing a census of the whole X-ray sky with unprecedented sensitivity.



↑ This next generation silicon detector with active pixel sensors could be part of the ATHENA+ mission proposed to ESA.

Times have changed in space astronomy since the pioneering days however: resources are scarcer, competition is stiffer and rockets aren't getting any bigger. This makes it harder than ever to get big projects off the ground, however exciting they are scientifically. Another change in the world of space, just as in most other spheres, is the emergence of major new players, beyond the established big agencies like ESA and NASA. This is taking us to new places – literally as well as figuratively.

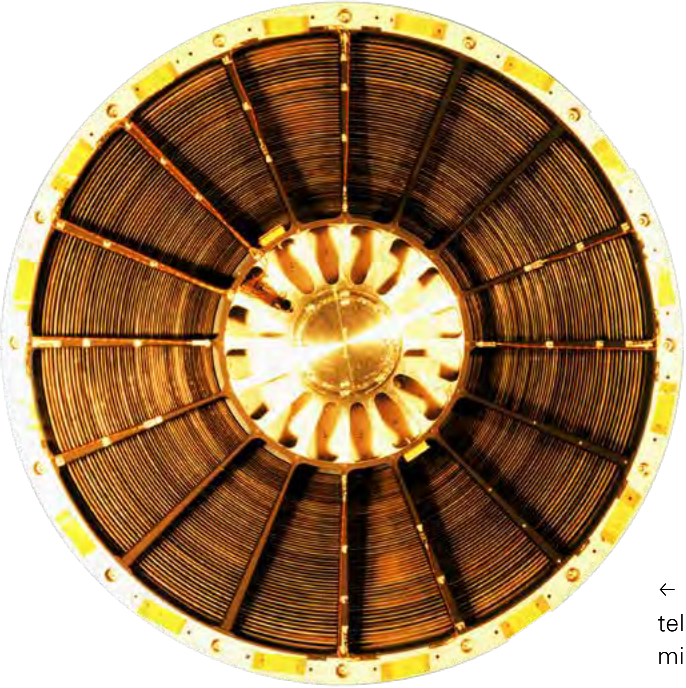
Moving beyond the amazing facilities we have today is a major challenge, but it's one we relish here at the Institute. Over the last few years we've been brewing up bigger, better and bolder ideas to take us into a new era. To make a compelling advance we need new technologies that can fit the



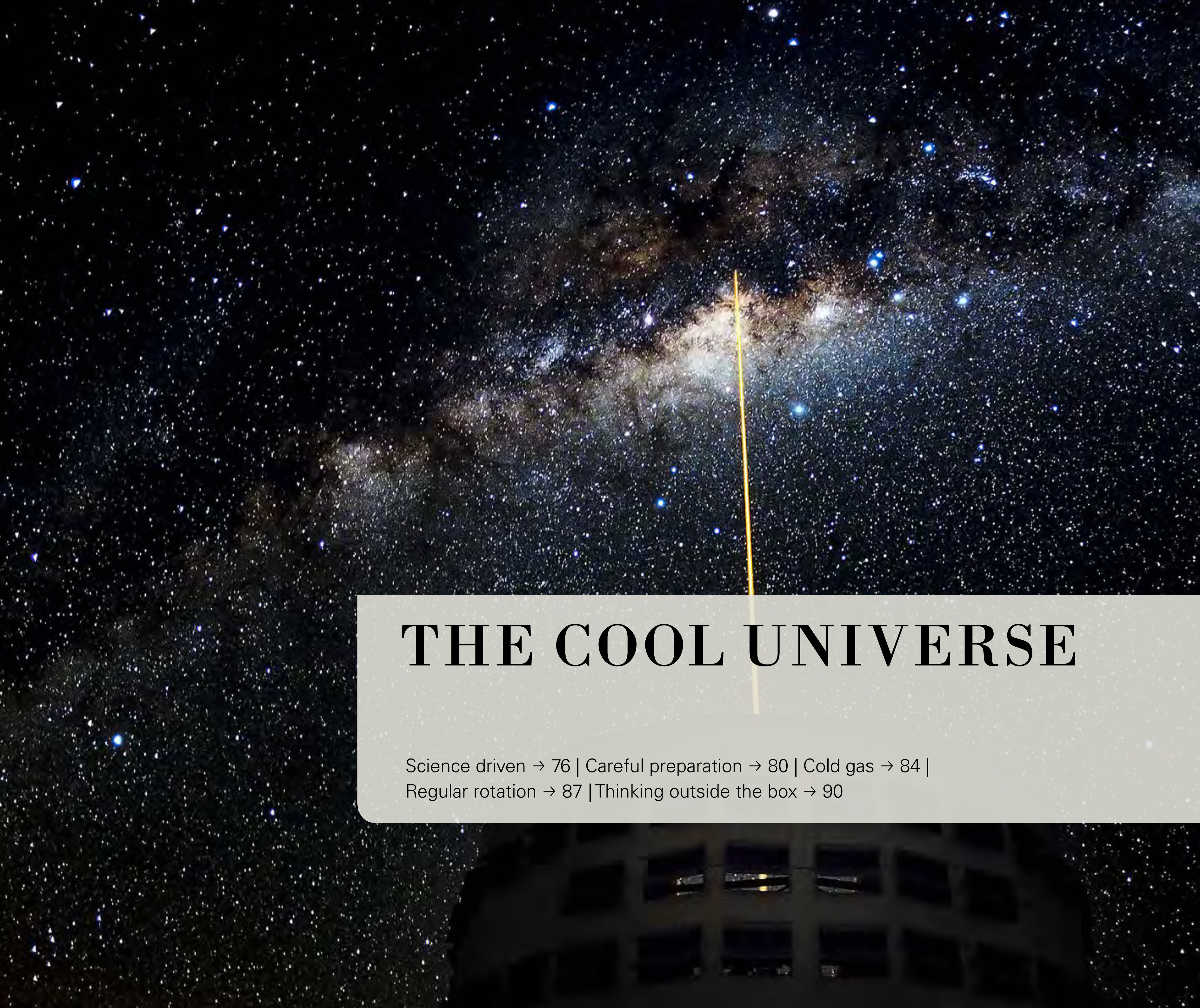
↑ Probing the formation of galaxy clusters. The colours in these images indicate the temperature of the internal gas of the clusters, and the brightness is a measure of the gas density. These measurements contain important information about physical parameters such as the gas density and their evolution over cosmic time.

same budgets we had before – whether they are measured in satellite mass, power or pure cash – while delivering new scientific breakthroughs. That means consistent investment and constant innovation of the type that MPE has been famous for throughout its entire history. With that, we can be confident of future successes to match those of the past.

If I'm lucky enough to be around for the hundred year anniversary, I'll expect to see more dramatic changes in high energy astronomy. The subject might have matured, but it's young and vital at heart. The beat goes on …



← Each of the three XMM telescopes contains 58 nested mirror pairs.



THE COOL UNIVERSE

← For the first years, the galactic centre was observed with the New Technology Telescope, which provided the sharpest possible images.

SCIENCE DRIVEN

Reinhard Genzel

The institute's foray into long wavelengths originally started with a small effort centred on balloon-borne astronomy and ground-based spectroscopy. With observations at high energies well under way, the astronomers wanted complementary information from the far-infrared range, which gives insight into different basic astrophysical processes, in particular the formation and evolution of stars and galaxies. In the mid-1980s, the MPE directors decided to boost this area substantially and brought Reinhard Genzel to the institute as its new director. He had worked with the Nobel laureate Charles Townes (now an external scientific member of MPE) in experimental far-infrared astronomy at the University of California in Berkeley.

Genzel brought a new philosophy with him: novel instrumentation was designed to specifically target key scientific issues. This approach blossomed over the following years with sophisticated instruments for ground-based and space telescopes being developed across the entire near-infrared to sub-millimetre wavelength range.

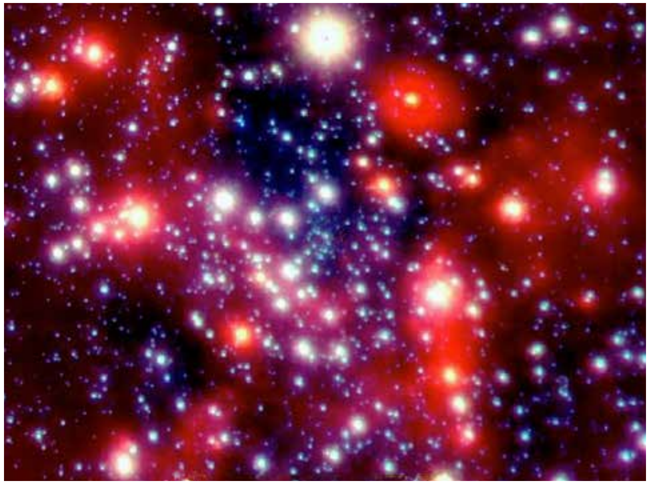
←← This image shows the Milky Way above one of the Very Large Telescopes together with a laser beam aimed at the galactic centre. The artificial star created by the beam allows the adaptive optics system to correct for the blurring effect of the Earth's atmosphere on astronomical images. This is especially important for extragalactic observations where there is no bright natural star close by.

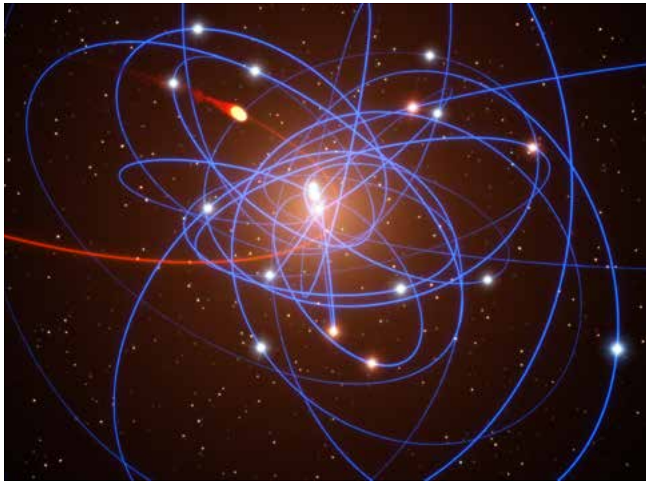
An excellent example of the successful scientific results achieved in this way is the galactic centre, where previous work had suggested the existence of a large central mass concentration associated with the Sagittarius A* radio source. The team then set out to show that this mass had to be a black hole with increasingly precise measurements.

Early spectroscopic observations indeed showed that the gas dynamics in this region were compatible with such a massive, very compact central object, but many astronomers were doubtful. There were too many processes such as magnetic fields, non-equilibrium effects, or winds that could possibly influence the motion of the gas. The ultimate proof was still missing, and this could only come from observations of stars.

> **“The ultimate proof could only come from observations of stars”**

→ Using the motion of stars in the centre of our Milky Way, astronomers could prove the presence of a gravity monster: a black hole of more than four million solar masses. In addition to the stars the astronomers found a gas cloud that is falling towards the black hole, being disrupted by the enormous gravitational pull.





→ The IR group around Reinhard Genzel is a close-knit team. Regular group meetings are essential for the lively collaboration between instrument and science teams.

These, however, were hidden behind dense clouds obscuring the galactic centre, which could only be pierced with infrared light. The aim therefore was to build a camera with a high enough resolution and sensitivity at long wavelengths to observe the stars around Sagittarius A*. An ambitious goal, as infrared detector development was still in its early days, with detectors measuring only a few dozen pixels on a side.

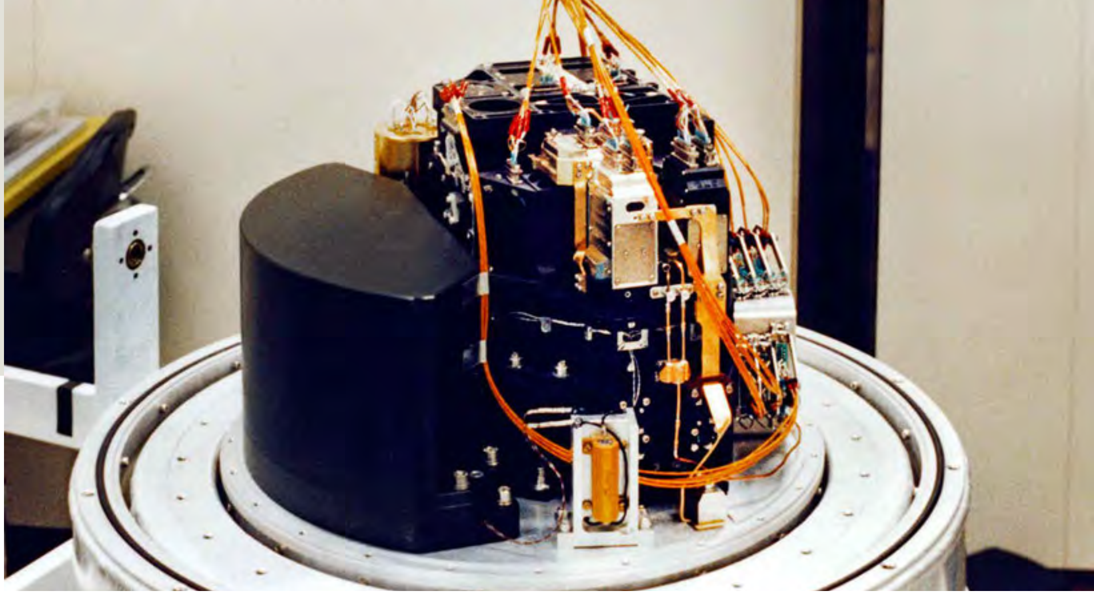
The breakthrough came with the NICMOS camera on board the Hubble Space Telescope: with 256x256 pixels this detector demonstrated that it was possible to reach the diffraction limit. For imaging from the ground, however, an additional challenge was the atmospheric disturbance. This atmospheric blurring causes stars to look like a smeared blob; with very short exposures, however, a diffraction-limited image could be reconstructed on a computer.

The technology, methodology (and funding) were now available or within reach, and the last major missing component was a large telescope combined with enough observation time to monitor the galactic centre for several years. An unsolicited proposal convinced the European Southern Observatory; and the New Technology Telescope, which was just starting its commissioning phase, was fitted with a novel high-resolution infrared camera (SHARP) developed at MPE.

In 1992, regular observations of the stars around Sagittarius A* commenced, and the astrometric measurements showed that a mass, three million times heavier than our Sun, was centred on Sagittarius A* and was contained within one light month, strengthening the black hole hypothesis. And a few years later, with the new 8-metre Very Large Telescope and even more powerful imaging and spectroscopic instruments developed at MPE together with colleagues at other institutes exploiting the new technique of adaptive optics, it even became possible to measure the orbits of the stars in the galactic centre. One star completed a full revolution in the first 16 years of the study and approached the central object up to a distance of only 17 light-hours. This data provided compelling evidence that the central mass cannot be anything but a black hole of 4.3 million solar masses as long as Einstein's general theory of relativity is valid.

← To probe the innermost region of our galaxy, close to the black hole, GRAVITY will use all four Very Large Telescopes at the same time as an interferometer.

While this settled the question of the existence of a black hole in our galaxy (and also strengthened the view that most other galaxies have a black hole at their centre), the next challenge will be observations on even smaller scales to test the gravitational potential close to the event horizon. This high spatial resolution and astrometric precision can only be achieved with interferometry, using all four Very Large Telescopes at the same time.



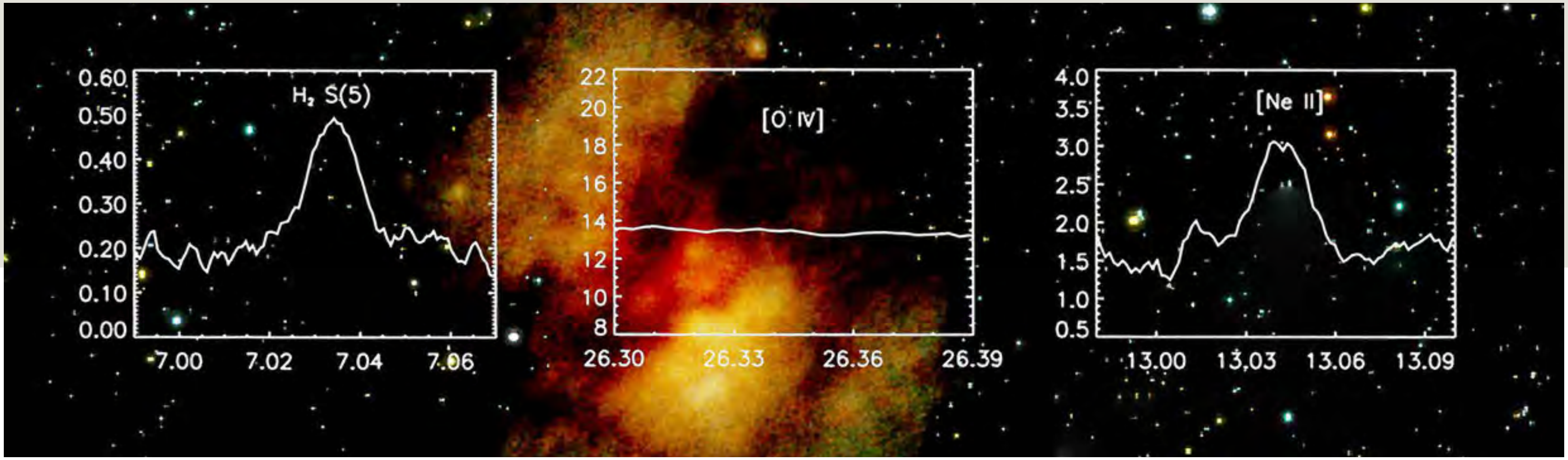
CAREFUL PREPARATION

Dieter Lutz

The Earth's atmosphere blocks some of the infrared radiation, and so in the 1990s, the infrared group started to work on instrumentation for the Infrared Space Observatory ISO, which was built in a Europe-wide collaboration. The hardware people were busy designing and testing the various components – finding and fixing defects such as a mirror that suddenly looked as if it had been splattered with droplets of oil but actually it had a faulty gold coating that had come off. At the same time, another part of the team was already preparing for the observations, interpreting the test data produced under controlled conditions in the lab and working on strategies for calibrating the instrument in the sky. The close teamwork between the scientific and instrumentation teams has always been the strength of the group – even outside of the core team; everybody shared their experience and knowledge.

← As one of four ISO instruments, the short wavelength spectrometer (SWS) provided unprecedented sensitivity and spectroscopic resolution in the micrometre wavelength range.

→ ISO was put into orbit by an Ariane rocket from the Kourou spaceport in French Guiana in November 1995.



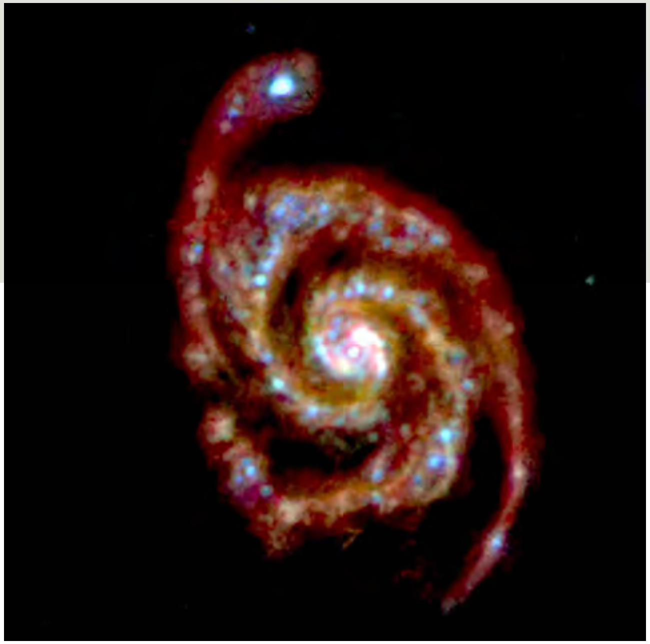
↑ In the ultraluminous infrared galaxy Arp 220, spectra taken with ISO have revealed the presence of emission lines indicating vigorous star formation. Infrared observations can penetrate the thick clouds of absorbing dust seen in the visible light image.

On 10 November 1995 the big date came. Basically the whole team had flown out to Kourou to watch the launch of the rocket. But after we were shown around the site in the morning, we learned that there was a problem with the rocket and that the launch had to be postponed for a week. While some colleagues stayed behind, I had to go back to the institute as quickly as possible to work on new sources for calibration, as the original ones would not be visible any more.

Still, one week later I wanted to watch the launch live, even though it was the middle of the night in Europe. We had made a deal with the BR Space Night (a TV programme showing recordings in and from space with music added) to instead show live coverage of the launch. The alarm went off, I switched on the TV, but nothing happened – there was only the regular programme. Later it turned out that the person responsible at the TV station did not have written confirmation of the agreement and therefore did not change over to the video feed from the launch site. I had to wait until the next morning, when the radio news reported on the successful launch.

ISO worked excellently for the next 2.5 years, until its liquid helium coolant was exhausted. With the large allocation of

↑ The ISOCAM image reveals the main star forming regions and the diffuse interstellar emission in the merging antenna galaxies.



→ The “whirlpool galaxy” (M51) was the target of the first test observation of the Herschel space observatory after the instrument cover had been opened. The infrared light shows clouds of gas and dust between the stars in the spiral arms.

guaranteed time that we received for our hardware contribution, we were able to focus on a few important, open questions, such as the power source of ultra-luminous infrared galaxies. Spectroscopic studies with ISO found that these are predominantly powered by intense starburst activities.

Back then, we were a small team and it was very easy to come to a decision about new observations. Collaborations have now become larger, and so the overheads have grown as well. Nevertheless, even now things sometimes still have to be more or less improvised: after the launch of the Herschel observatory, ISO’s grandchild, the European Space Agency wanted an image for the media right away. At the time we did not know where the telescope was pointing or which settings to use for our instrument, but the observation had to be made somehow. So we made a lucky guess and just tried a few numbers – and a short time after opening the telescope cover we knew that our instrument was working properly and was in focus!

← The Plateau de Bure millimetre interferometer in the southern French Alps provides high-resolution radio images and spectra.

↑ This image shows a typical massive galaxy about 5.5 billion years after the Big Bang. While the optical image (green) shows some evidence of young stars in the spiral arms, the molecular gas visible at long wavelengths is about ten times more than in typical disk galaxies today.

COLD GAS

Linda Tacconi

If an observation is easy, others will do it, so the real challenge is to do something difficult. Pioneers explore not only new technologies but also push the frontiers of science. The IRAM observatory on top of the Plateau de Bure in France is a prime example. Today it consists of six 15 m-telescopes used in concert as a radio interferometer. However, when construction work started at the beginning of the 1990s, other groups had a head start and had already obtained first results from their interferometers.

> “Other groups had a head start but we soon caught up”

With fewer but bigger antennas, the Plateau de Bure interferometer (PdBI) soon caught up and it was then possible make sensitive extragalactic observations. We decided that it was a perfect complement to the instruments being built in-house. Scientifically it would provide crucial information about the cold gas content and star formation in galaxies. Our first result with only three antennas on Plateau de Bure was a study of a

→ In the 1990s, the infrared group built a test receiver for the 30-metre IRAM telescope on the Pico Veleta in Spain.

↑ The ALMA radio interferometer consists of 66 telescopes with 12 and 7 metres in diameter. With its higher sensitivity and resolution it will allow detailed studies of gas clouds and star forming regions in galaxies.

nearby Seyfert galaxy, where we found evidence of dense gas that might be feeding the nucleus, leading the way to many more observations of nearby galaxies and active galactic nuclei.

The subsequent extension to six antennas as well as the use of upgraded instruments allowed us to venture into the distant universe, observing especially bright objects first of all. Observations that would have taken several nights could now be completed in a few hours. The PdBI has been the leading facility for studying early universe galaxies at millimetre wavelengths – and we always collaborated closely with the others in the group who were doing cutting-edge observations in near and far infrared wavelengths.

The shift to the distant universe came very naturally to me as I had worked in extragalactic astronomy before and also because the focus of the science of the infrared group as a whole had changed as facilities such as ISO in space and then SINFONI at the VLT produced truly revolutionary results. And now we will again be pushing the limits using the next generation of observatories to bridge the gap and study galaxies as they mature.

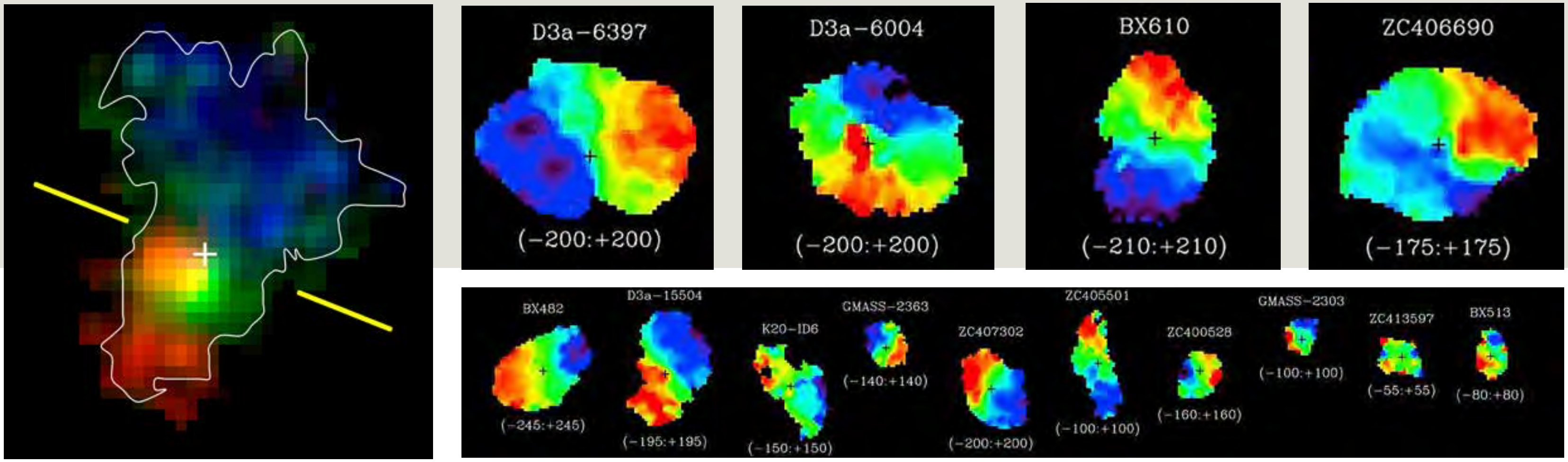
→→ The SINFONI instrument mounted on one of ESO's Very Large Telescopes consists of the SPIFFI Integral Field Spectrograph, developed at MPE, and an adaptive optics module. This allows astronomers to simultaneously observe images and spectra of objects in a small sky field.

REGULAR ROTATION

Natascha M. Förster Schreiber

After observing and mapping nearby starburst galaxies with earlier near and mid-infrared imaging spectrographs, the higher resolution and sensitivity provided by SINFONI made it possible to apply the same detailed studies to distant galaxies: What kind of galaxies are they? What is the distribution of young star-forming regions and of older stars and how do they move?

We were in for a surprise. At the time, observations and cosmological models of galaxy evolution had led astronomers to favour a scenario in which galaxy evolution is mainly driven by mergers with violent disruptions and increased starburst activities. But what we found was that the majority of distant galaxies turned out to have a disk-like structure with a fairly ordered rotation. These disks had not been disturbed strongly; processes within the disks themselves must have dominated. Therefore our picture of the life cycle of a typical galaxy has changed: gas is accreted rather smoothly onto nascent galaxies, it is then partly transformed in situ into stars, and eventually enriched material is pushed away by stellar and galactic winds.

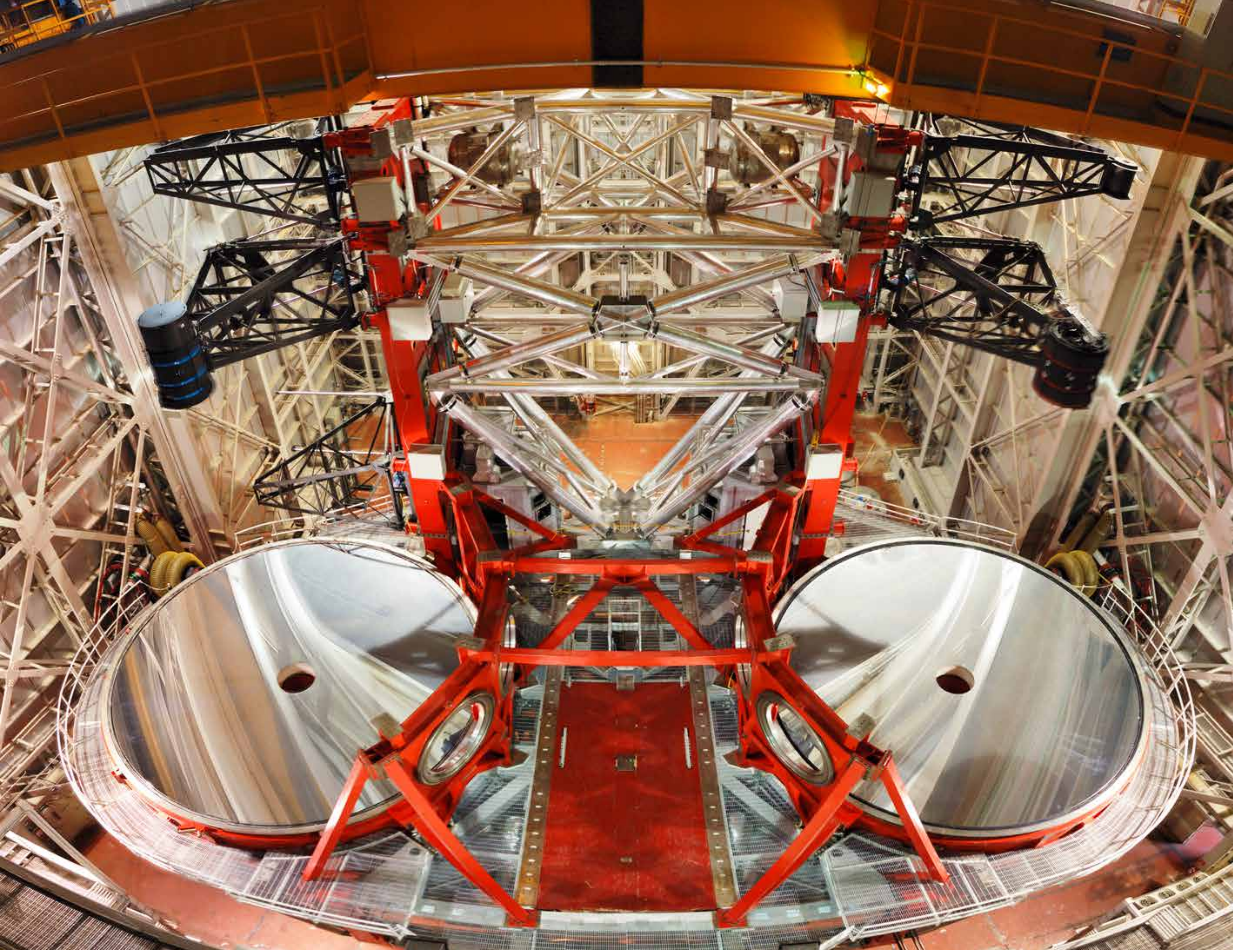


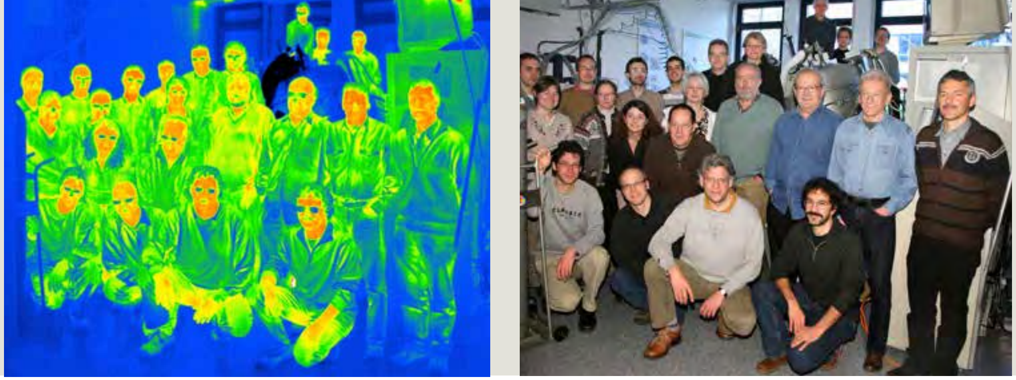
↗ The colours in these images of far-away galaxies indicate motion: The ionised gas is moving away from us (red), toward us (blue) or is stationary (green), relative to the overall rest frame of the galaxy. It was very surprising to find such a disk-like structure already three billion years after the big bang. The galaxy shown left was one of the first distant objects observed by MPE scientists with SINFONI and adaptive optics.

Even more detailed SINFONI observations using adaptive optics confirmed this picture and revealed some of the more subtle features such as large and intensely star-forming clumps, powerful gas outflows, and young bulges. These findings together with recent evidence from observations at other wavelengths provide new and crucial insights that constrain theoretical models of galaxy evolution. But while each successful project answers some questions, it also poses many new questions that need to be tackled with even more powerful instruments. One such instrument is KMOS, a multi-unit imaging spectrograph that now allows us to investigate distant galaxies, much like with SINFONI but with about 20 times more objects in one go! This will give us a much more complete picture of how galaxies assembled and then became the galaxies that we can see today.

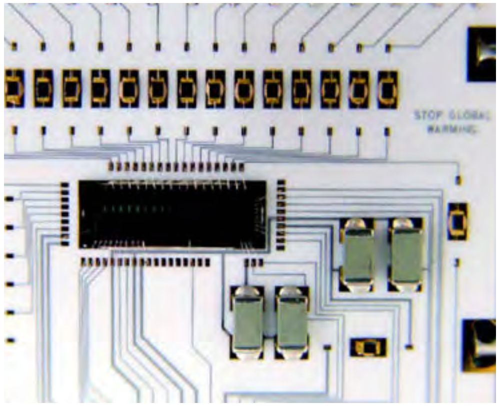
A close synergy is essential between the instrumentation and the science that is being done. Instruments are developed to address specific key questions, during the study one stumbles over unforeseen findings and more questions arise, while at the same time advances in instrumentation open up new horizons. But being part of a group that is developing an instrument not only means that the instrument is optimized for a specific goal, it also brings the additional benefit of guaranteed observing time. This means that one can invest in doing an extensive programme, not just doing things piecemeal.

→ The Large Binocular Telescope, with two 8.4 metre primary mirrors, provides exceedingly sharp images due to its special configuration.





← Infrared and optical image of the PACS team.



↑ This silicon chip has to operate at 2 Kelvin (–271°C) and therefore needs a special circuit design. It took seven generations of development until a working configuration was found.

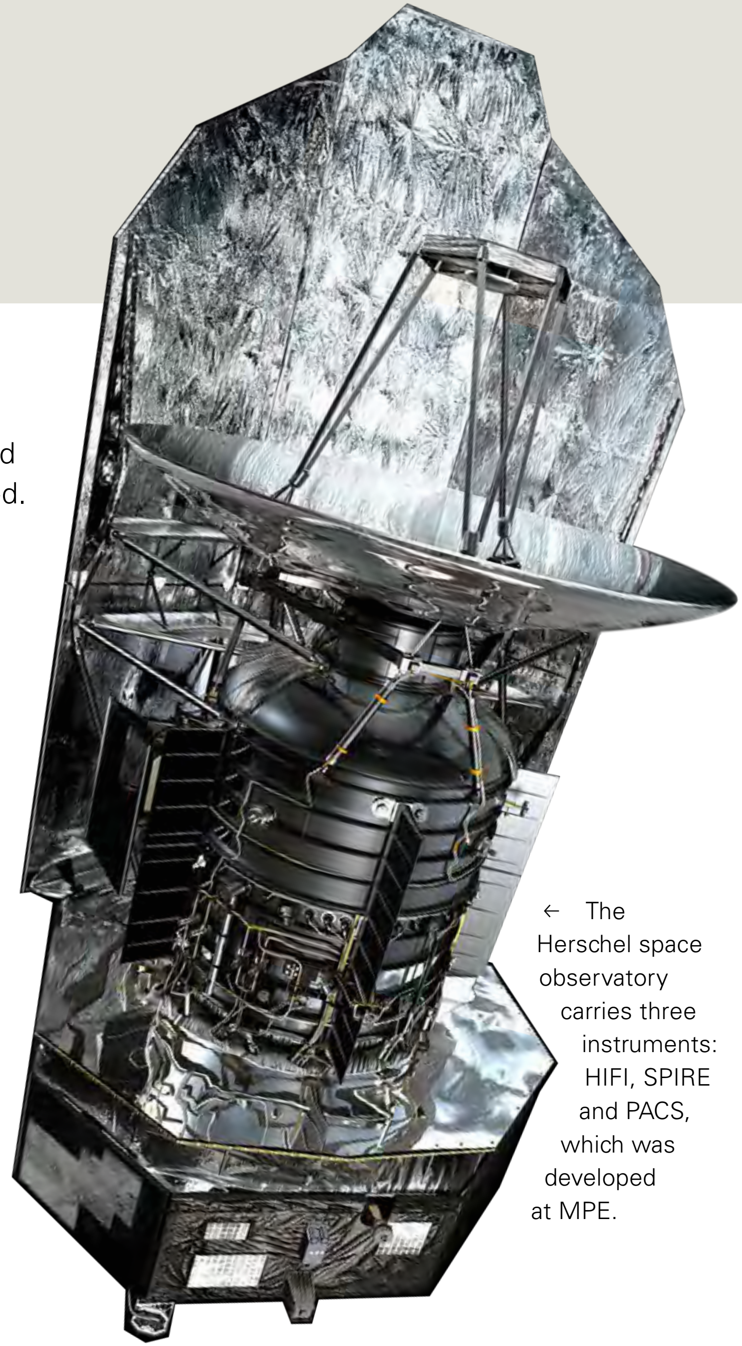
THINKING OUTSIDE THE BOX

Albrecht Poglitsch

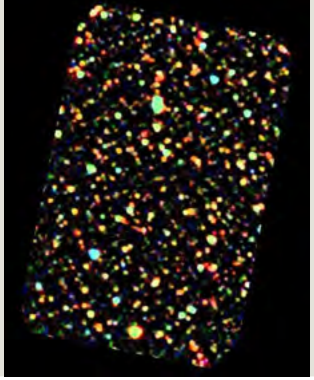
With its 3.5 metre mirror, Herschel was the largest telescope ever flown into space, and PACS was one of the most complicated instruments ever built at MPE. Just to start with the detectors for the spectrometer: each of the 16×25 entrance “horns” concentrating the incoming light onto each single pixel had to be individually shaped as the optical system was extremely compact and the focal plane had to be arranged on a curved surface. The total optical path of 4-5 metres had to be folded to fit into an envelope of less than one metre in diameter, and as the instrument incorporates two, almost completely separate paths for photometry and spectroscopy, there were 72 mirrors in total, many of them non-standard optical surfaces. When asked how the team would be able to properly align all these individual components, the standard answer was “with care”. And indeed, by organising the whole system into subunits, the whole optical train did what it was supposed to do.

At least until the last test run in the lab, when all of a sudden the infrared point sources used to test the camera suddenly appeared peanut-shaped. Worried, the team had to continue with the test schedule as the instrument had been cooled down to its operating temperature of below 2 Kelvin (–271° Celsius) and the delivery date was too near to allow another full temperature cycle. Only a couple of days later, when PACS was back at room temperature and the cryostat could be opened, everybody breathed a huge sigh of relief: it had been forgotten to remove a protective foil before cool-down, and this mistake could easily be remedied. The team could thus hand over their instrument to be integrated with the satellite.

This was not the first scare in the development of PACS. It had all started about a decade earlier, when the proposal of a new, large space-borne infrared observatory was accepted by the European Space Agency and the infrared group started to work out the details of their hardware contribution right away. In 2000, however, it became clear that the planned combination of photoconductive detectors and electronic readout chips would work well for spectroscopy, but would never be able to handle the high fluxes seen in photometry. So what to do?

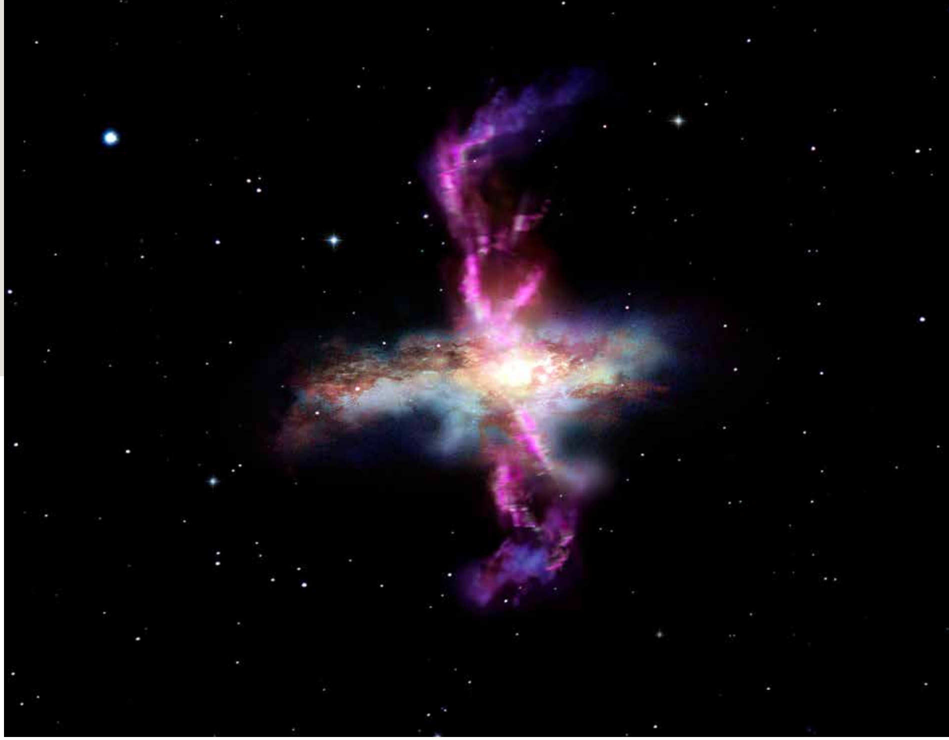


← The Herschel space observatory carries three instruments: HIFI, SPIRE and PACS, which was developed at MPE.



→ Gigantic storms rage in the centres of many galaxies blowing massive amounts of molecular gas into space.

↑ With the deep images taken of regions such as the GOODS field, Herschel was able to resolve most of the infrared background into individual sources.



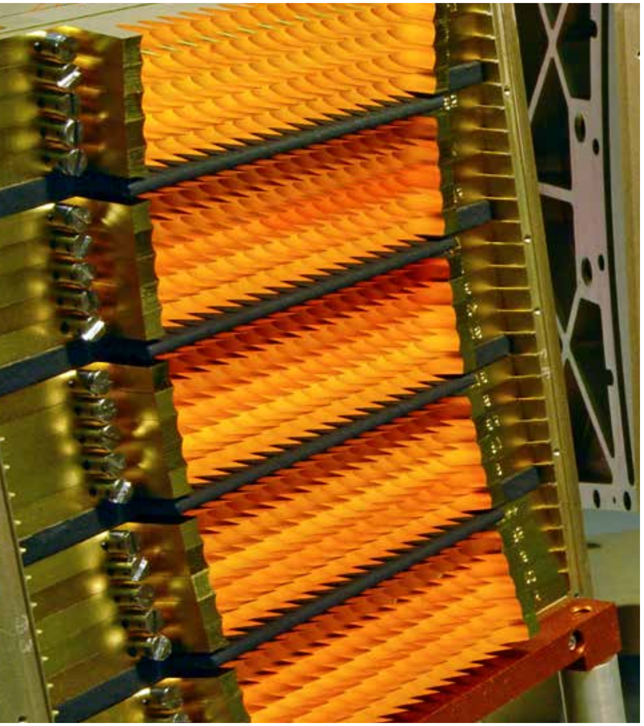
By a lucky coincidence, a French group offered an imaging detector for another project that the infrared group was working on simultaneously at that time. It did not fit there, but maybe it would work with PACS. A crazy idea, but when the two teams met a couple of weeks later, they found that success was "not excluded". And indeed after several months of working around the clock they found a workable configuration. Now PACS was functional and promised to deliver the expected scientific results.

Even though there were some bumps on the road to the final instrument, once it was launched into space in 2009, PACS worked beautifully and even exceeded expectations. Peering deep into the universe it was able to resolve the diffuse infrared background emissions into individual sources and showed that stars are formed continually, not predominantly in bursts triggered by galaxy mergers, as astronomers had

> **"Success was not excluded"**

←← Peering into dense clouds of gas and dust, Herschel can directly image stellar nurseries such as the Rosette nebula seen here.

← All components and in particular the intricate optics design of PACS had to be carefully tested.



↑ Each of the 400 detector pixels consists of a light-concentrating cone and a highly sensitive gallium-doped germanium photoconductor crystal.

assumed before. Detailed images of gas clouds and star forming regions also revealed how initial clumps form and grow into stars of different sizes, with a large portion of the gas being lost due to turbulence and winds.

After nearly four years, the liquid helium coolant on-board the Herschel satellite was finally exhausted and the instrument was switched off. The wealth of data collected, however, will keep astronomers busy for many years to come.

→ The Hubble Ultra Deep Field is a very deep image of a small region of space, looking back about 13 million years. With a total exposure time of a bit less than 1 million seconds (or more than 11 days) very faint and distant galaxies are visible, showing a wide variety of shapes and structures.

EYES ON THE SKY

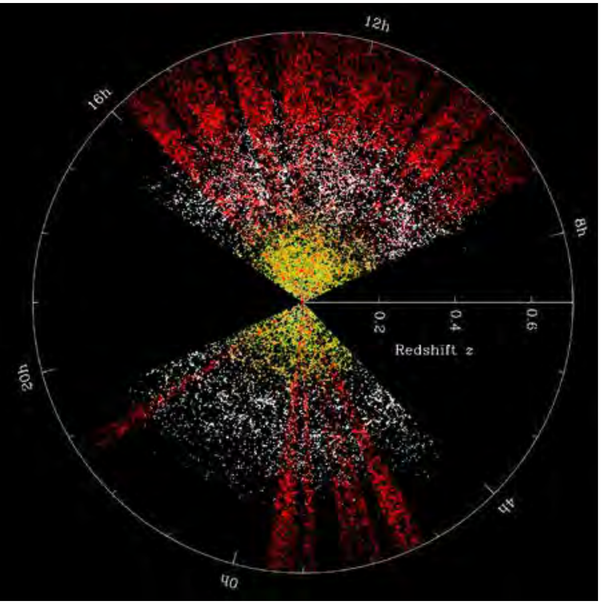
↑ Ralf Bender in discussion with Werner Becker.

↗ Group meeting at castle Ringberg.

A SMOOTH BLEND

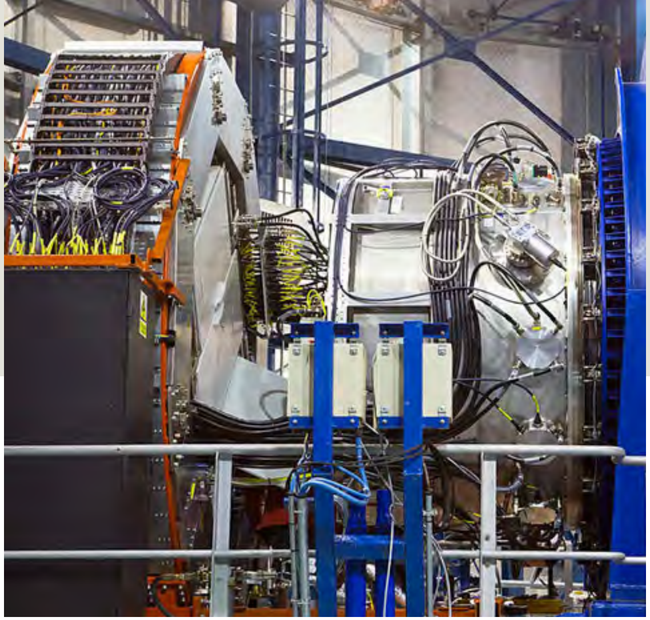
Ralf Bender

Science is top priority for both a university and a Max Planck institute, but despite many similarities, you sometimes get the impression that you live in two different worlds. So, when MPE offered Ralf Bender a directorship at MPE in addition to his professorship at the Ludwig-Maximilians University, he wondered how the two worlds might come together. In the end, it went surprisingly smoothly. Maintaining a joint group at both institutions wasn't too difficult, although ensuring coherence requires some investment. Modern technology helped a lot. Thus, one of the very first investments after the appointment went into a video-conferencing system that enabled joint seminars without having to deal with the burden of Munich's traffic.



← This pie-diagram shows the three-dimensional distribution of massive galaxies in the sky, obtained by the BOSS survey. From the distribution of these galaxies, the scientists can infer constraints on the mysterious dark energy, which today accelerates the expansion of the universe.

→ With KMOS mounted on the VLT, astronomers are now able to observe 24 galaxies at once and map the properties of each simultaneously. Large, detailed galaxy surveys can thus be completed over a relatively short time.



An easy start at MPE was also possible because office space had just become available as the old part of the MPE building had been freshly renovated and the group could settle in straight away and start growing. While collaborations between scientists at MPE and the University of Munich's observatory had existed before, the contacts now intensified and led to large joint programmes, both for developing instrumentation and exploiting its capabilities to answer important scientific questions.

The flexibility and stability of funding at Max Planck institutes obviously proved to be very advantageous. Among many new project opportunities, the possibility of inviting short and long term visitors more easily benefitted science quite considerably. In 2012, one of the regular summer visitors, long-term collaborator John Kormendy, even became an external scientific member of MPE.

But the University also contributes as equals to the success of the OPINAS group. We have access to the 9-metre Hobby Eberly Telescope in Texas and the 2-metre Fraunhofer Telescope on Mount Wendelstein

→ The light of distant galaxies is collected by 24 pick-off arms, which can be freely moved in the field of view of the Very Large Telescope.

↑ The nucleus of the Andromeda galaxy has a very complex structure with a supermassive black hole (with about 140 million solar masses) at the centre. The analysis of the white-blue stars shows that they are surprisingly young and form a disk, which rotates with more than 1000 km/s around the black hole.

through the university's observatory. The technical staff there is crucial for the group's successful ground-based instrumentation programme, be it for the ESO Very Large Telescope or other telescopes. And, of course, the university offers easier access to students who provide stimulus and sometimes even trigger new research directions.

So, there is a lot of give and take between the two worlds.

ON TOP OF THE MOUNTAIN

Ulrich Hopp

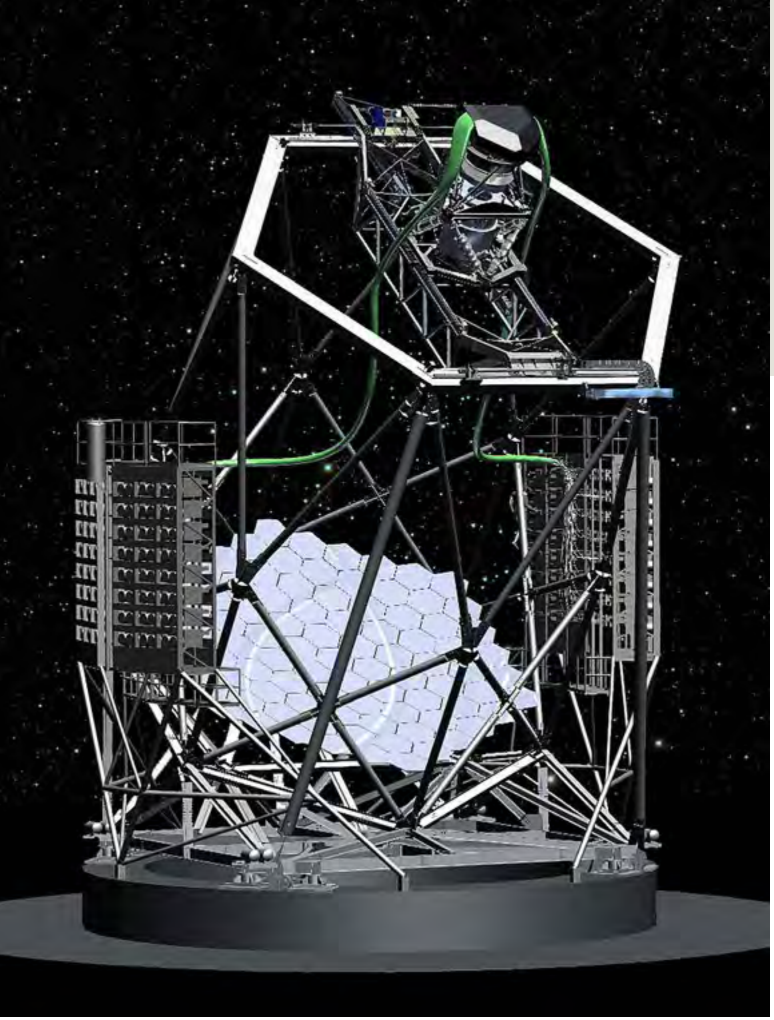
Big astronomy often needs big observatories, but smaller telescopes can score with their own unique advantages. As the Wendelstein observatory, for example, is operated by the Ludwig-Maximilians-University in Munich, the astronomers do not have to compete for time with other groups. Out of the 120 clear nights per year, almost all can be spent on a few selected projects such as monitoring variable objects, searching for planets, or exploiting gravitational lens effects when detecting so-called MACHOS.

With the close collaboration between the university observatory and the OPINAS group at MPE, new interesting questions arose as well as new ideas for joint projects across different wavelengths. The Wendelstein observatory can be used for all kinds of follow-up observations such as photometric redshift estimates for galaxy clusters found in surveys like Pan-STARRS or eROSITA.

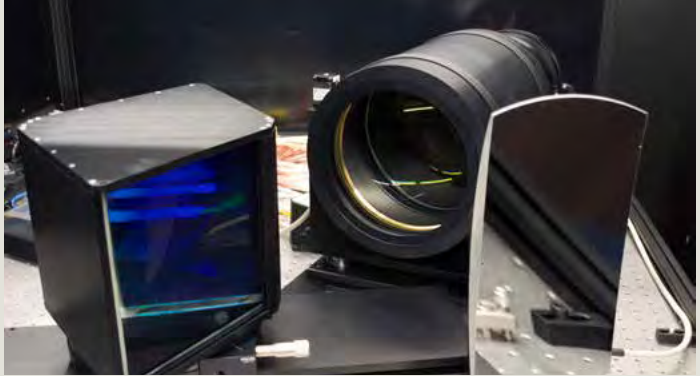
↑ All the components and equipment for the construction of the Wendelstein 2-metre telescope had to be airlifted.

In 2005, the university decided to install a 2-metre class telescope on top of the Wendelstein mountain – the largest telescope that could fit into the observing dome on top of the peak. Almost all components needed to be airlifted to an altitude of 1838 metres, requiring good weather for hundreds of flights with a helicopter capable of airlifting 1.6 tons and also a few with a heavy-duty helicopter that transported the large sections of the dome and the telescope mirror, which weighed 4.5 tons with its hoisting platform.

The observers will have the choice between four main instruments, which can be interchanged flexibly. A wide-field imager with a very large field of view and few disturbing reflections can be used for observing galaxy clusters or our neighbouring Andromeda galaxy; a medium-resolution field spectrograph will allow studies of galaxy dynamics. This instrument, called VIRUS-W, was developed at MPE especially for use at the Wendelstein



↑ The Hobby Eberly telescope with the completed primary mirror. The HET Dark Energy Experiment will consist of 150 identical spectrographs attached to the telescope.



↑ In the VIRUS-W spectrograph a bunch of optical fibres guide the light to a high-resolution grating so that spectra from many points in the sky can be obtained simultaneously.

observatory, although it is based on a series of 150 lower-resolution spectrographs designed for another large-scale cosmological project. In this international collaboration, cosmologists from MPE and the university observatory will use the HET telescope of the McDonald observatory in Austin, Texas, to determine the expansion history of the universe from the three-dimensional distribution of galaxies.

The VIRUS-W spectrograph (W for Wendelstein) will focus more on galaxies in the nearby universe, mapping the motion of their stars. While waiting for its integration at the Wendelstein observatory, the VIRUS-W spectrograph is not idle: in the meantime is has been installed at the 2.7-metre telescope in Texas, where it has already produced the first images of spiral galaxies.

← The McDonald Observatory in Texas works closely with the University Observatory Munich and the MPE.

NIGHT OBSERVATIONS

Roberto Saglia

↓ The gigapixel camera on the Pan-STARRS1 telescope.

Astronomy is fascinating – and this fascination attracts a steady stream of graduate students. The university as well as the regular lectures are an ideal recruiting ground in addition to the international students that arrive via the IMPRS research school. The students are able to choose between a wide variety of topics and methods. Even for the more theoretically oriented students, however, there comes a point when they want to do some observations themselves. And it is indeed a great experience to travel to a large telescope, such as at the McDonald Observatory in Texas, which uses instrumentation that was developed here.

The 2.7-metre McDonald telescope is one of the old guard, the best way to learn how to observe properly. Here an observing night is not just a boring sequence of commands typed at the console to move the telescope to the correct object, to open the shutter of the instrument, to wait until the exposure time has finished and then to take a reading from the detector. Often alarm





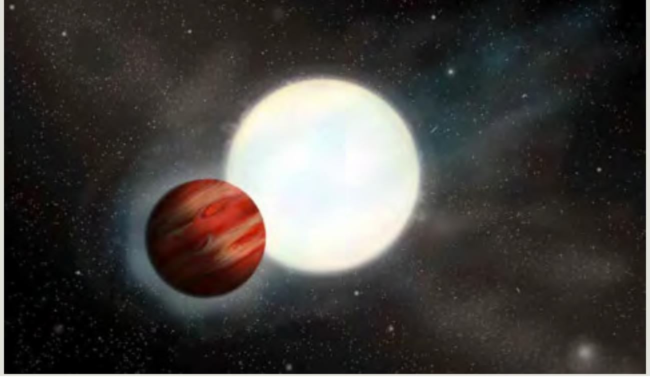
↑ For most astronomy graduates there comes a point, when they want to go observing – a very special experience.

bells ring because the telescope has almost hit the wall! You then have to run into the freezing dome and move the telescope out of danger manually. Sometimes it is the rain that forces you to close up everything in a hurry. During a good night, however, you can relax during a long exposure and go out onto the catwalk to enjoy the dark skies of Texas. No student regrets such an experience.

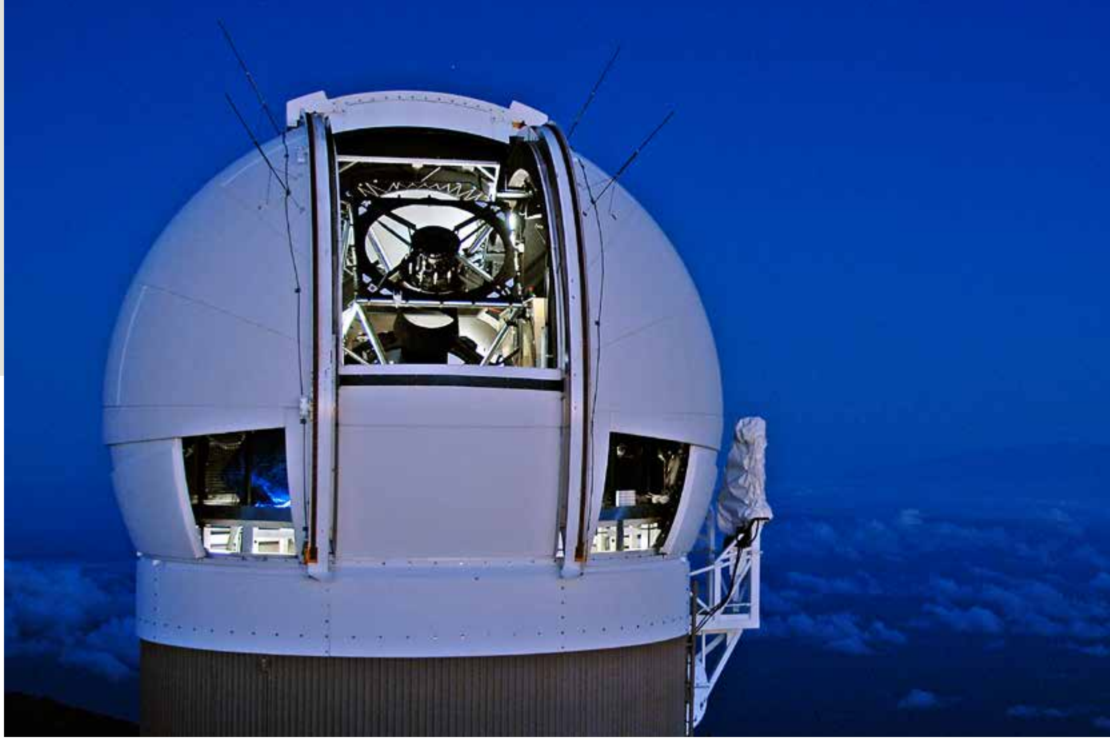
> “During a good night you can relax and enjoy the dark skies”

Joining the students on such an observing campaign is always great fun and an ideal opportunity to really get to know them, with all their strengths and weaknesses. These shared trips certainly contribute to the familiar atmosphere and good companionship within the group. Many of the students continue and extend their successful projects after they have completed their PhDs and even if students do move on to other institutes they stay in touch.

What started off as a small student project can thus find much more widespread applications for example as was the case of a software development for microlensing studies. The search for massive, compact objects is based on the fact that a star shines more brightly if a large mass passes



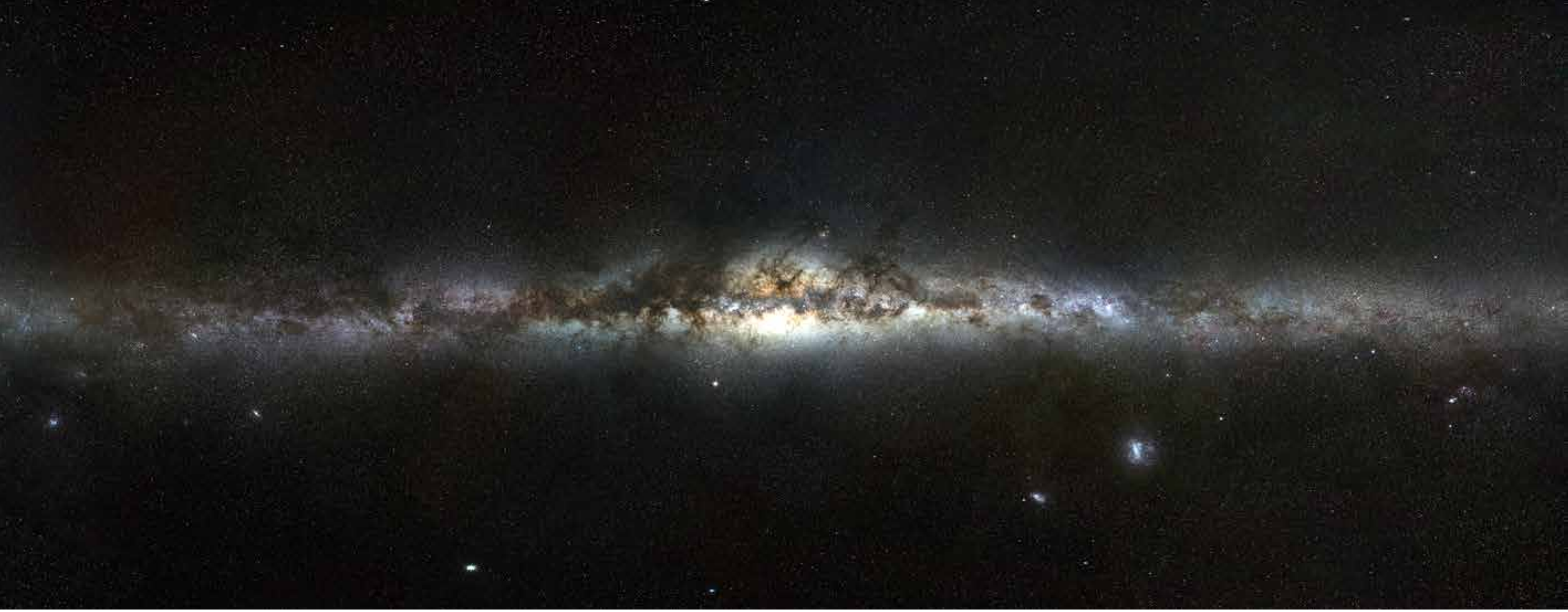
↑ An artist's impression of the WTS-1b planet in orbit around its host star, a "hot Jupiter". Its detection provided new input to theories of planet formation.



↑ The Pan-STARRS system combines relatively small mirrors with large digital cameras, which means that it can observe the entire sky several times every month. While the major goal is to search for asteroids and comets coming close to Earth, its huge database is ideal for research on objects that show some kind of time variability.

in front of it, due to the gravitational lensing effect. The software therefore had to analyse a sequence of images and, using difference imaging, search for brightness variations. The same principle also applies to the search for exoplanets using the transit method, where the light of a star is dimmed while a planet passes in front of it. The only major difference between the two is the timescale: for microlensing, observers take one image a day for a month, for planet searches it is more like one image per hour.

Once a candidate planet is found, follow-up observations determine the radial velocity and thus the mass of the planet. And another former student project now plays a role in the analysis of the dynamics of the planetary system, as the underlying physics is the same as for stellar dynamics in galaxies. Looking back, it is sometimes amazing how everything fits together!



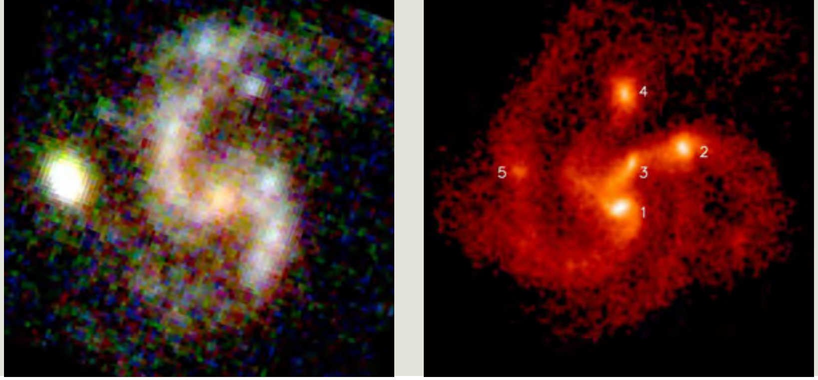
↑ This 360-degree panoramic image, covering the entire southern and northern celestial sphere, shows the disk of the Milky Way, where many stars of the bulge are hidden behind filaments of absorbing dust.

CLUMPY SPIRALS

Ortwin Gerhard

Today, astronomy is largely a collaborative enterprise, and there are many joint papers from experimentalists and theoreticians across institutional and national boundaries. Even at MPE itself, there are several theoretical groups, working on numerical models to understand the observational data.

One example of cross-fertilization between observations and theory was the detection of "clumpy galaxies" a decade ago. These far-away galaxies did not appear as smooth as predicted by the standard paradigm of galaxy formation, where matter collects in a dark matter halo, collapses and starts to form stars once the gas has cooled and becomes dense enough.



→ Clumpy galaxies were detected in the late 1990s, such as this by the Hubble Space Telescope (left). The star-forming disk model (right) was able to reproduce the striking features.

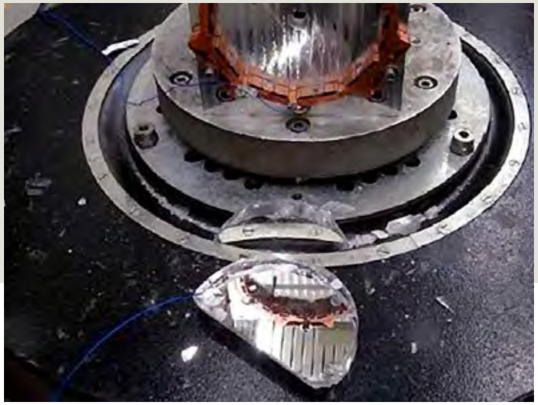
Irregular structures only arise in mergers in this framework, but the tell-tale signs of galaxy-galaxy interaction were missing in these clumpy galaxies.

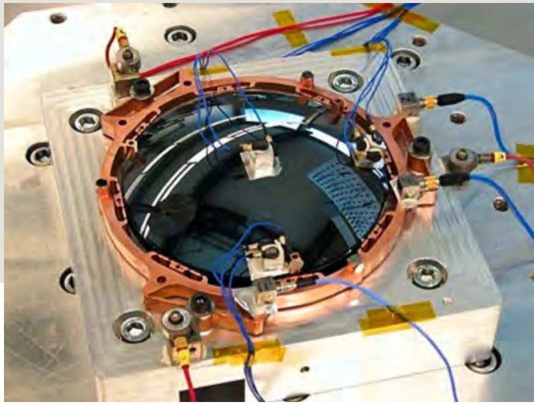
An alternative model was presented during a symposium about the Secular Evolution of Galaxies held at Ringberg castle in 2004: If a disk galaxy system contains a lot of gas and young stars because gas rapidly "rains down" onto the disk, then once the mass of the gas passes a certain threshold, the disk becomes unstable and starts to form clumps. Today's galaxies would not show such clumps, as they are farther along in their evolution with more of the gas either lost or locked up in stars. At that time, other theorists did not take this model seriously but looked for more conventional answers within the standard paradigm of galaxy evolution, such as mergers between galaxies.

However, at MPE a new observational project was starting with the goal of mapping the detailed structure of young distant galaxies and the researchers were interested in the instability model for clumpy galaxies. Over the next years, their detailed observations of young galaxies established that these galaxies were indeed less regular than today's more mature galaxies. In parallel, the astronomers mapped the relative motions and spatial distribution of the gas and stars within dozens of distant galaxies and revealed evidence of rotating stars in a disk, showing that clumpy disks were indeed common in early epochs.

← The NGC 1073 galaxy is a spiral galaxy with a bar-shaped bulge in the middle as in the Milky Way.

This raised several new and challenging questions: How did such ordered motion develop in galaxies so early in the universe? How did the clumps evolve, and would they last long enough to spiral into the centres of these galaxies and then form a central bulge? Answering these questions requires, on the one hand, collecting more information about galaxies over cosmic timescales with new instruments, and on the other hand, developing new theoretical models of galaxy evolution to match these observations.



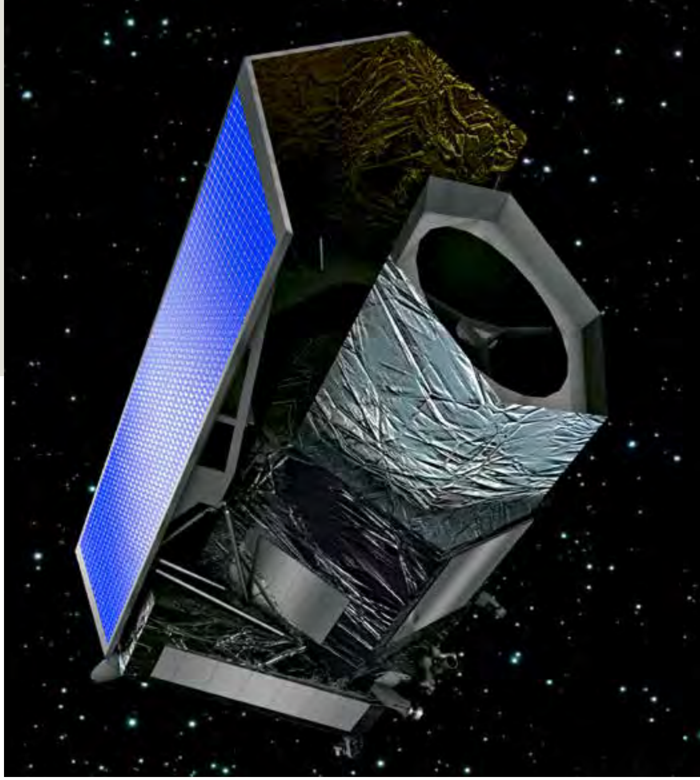


BAD LUCK OFTEN BRINGS GOOD LUCK

Frank Grupp

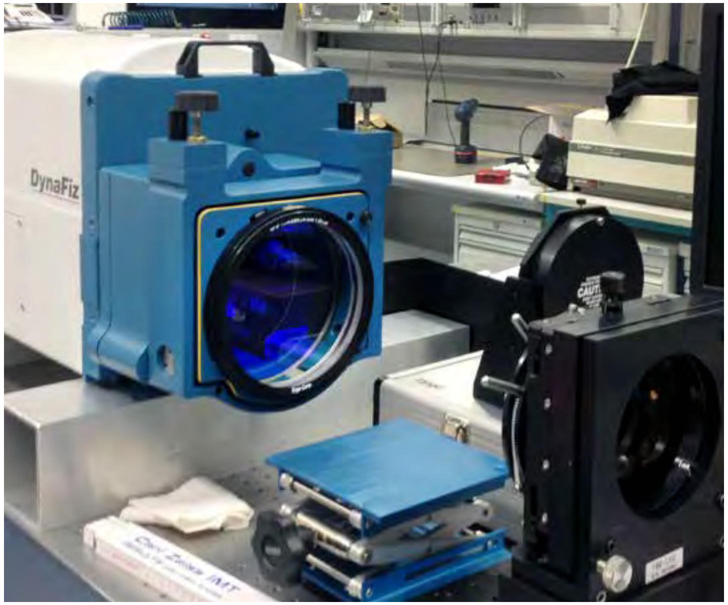
At the very beginning of the hardware development for EUCLID we managed to break the central optical component: during a vibration test, the lens shattered into a thousand pieces. Bringing such a large lens (which weighs about two kilograms) into orbit is definitely a challenge. Even though EUCLID's telescope mirror will be relatively small (having a diameter of 1.2 metres) the near-infrared optical system will contain the largest optical lens ever flown in space. Because of the large field-of-view of the telescope, an optical system based on mirrors would not fit onto the satellite and so the decision was taken to use the classic optical system. The fact that the first lens broke was actually a stroke of luck: in this way, a critical weakness was identified early on and remedied, the new lens is now made with a different glass mixture.

← Broken glass was the result of the first vibration test, the second lens is much more sturdy.



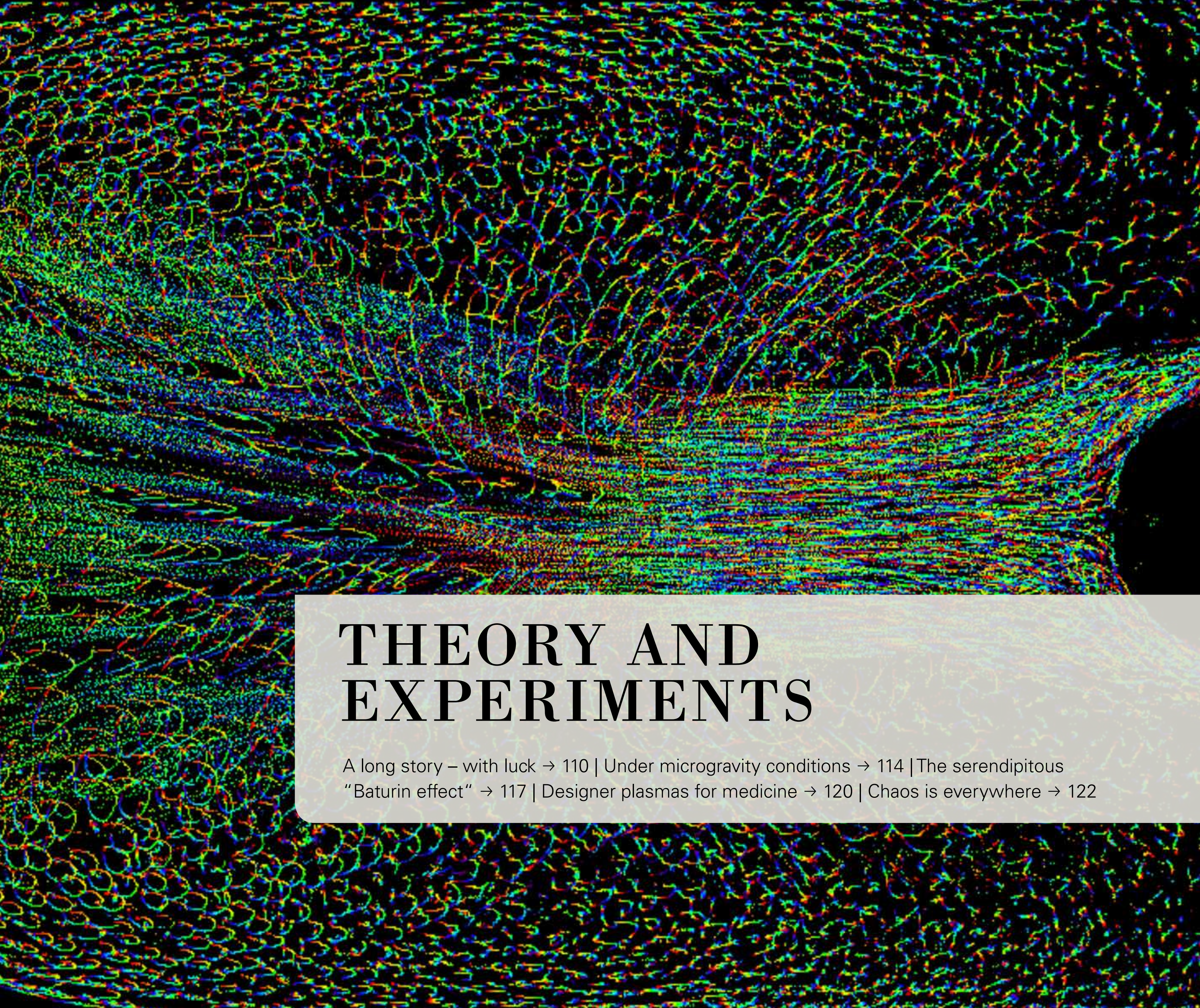
↑ The EUCLID observatory will perform a full-sky survey at the second Lagrange point L2, far away from the disturbing influences of both the Earth and the Moon.

But even if the optical system is a based on a classic design, there are many aspects that are far from classic. Because of the large field-of-view, the system has to be aligned to a precision of micrometres – at an operating temperature of about 140 Kelvin. At room temperature it is totally skewed, but despite that, the change of position during cool-down can be measured with a special cryostat. The final adjustments are then made with interferometric and holographic measurements in a new two-section clean room that houses the new coordinate measuring device.

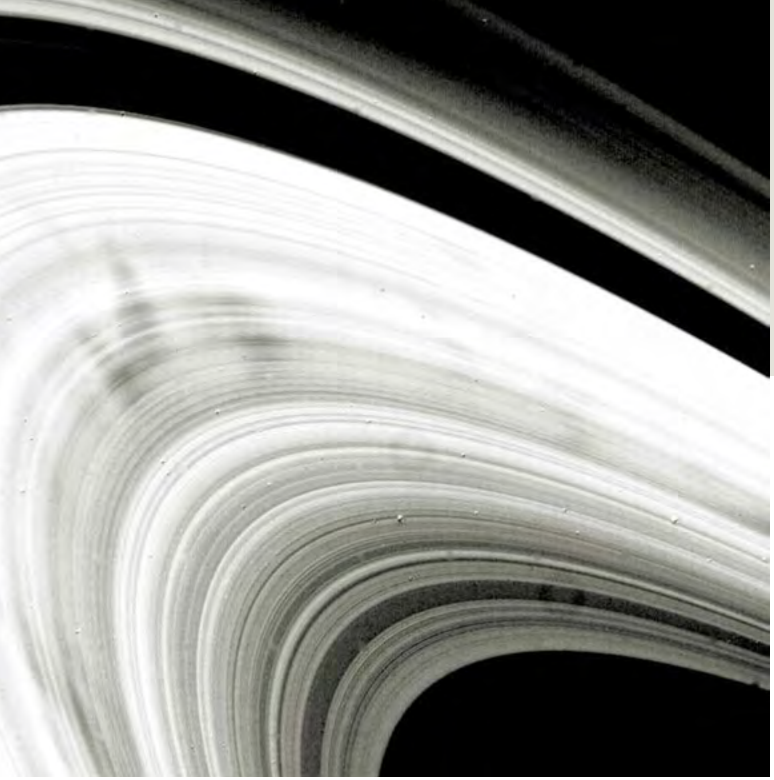


← A special coordinate measuring device can determine the quality of the alignment of all the optical parts to within a precision of micrometres.

In parallel, work has begun on processing and analysing the data expected from the telescope. EUCLID's main target will be the shapes and distances of far-away galaxies looking back up to 10 billion years. Over the course of several years the optical camera will map a large part of the extragalactic sky – leaving out the dense band of our Milky Way. For distance measurements a near-infrared camera and a spectrometer have also been included, whose data will be complemented by information from ground-based observations. Strategies for merging the different data sets and indeed managing the huge amount of data need to be developed so that in the end astronomers will obtain three-dimensional maps of the galaxy distribution.



THEORY AND EXPERIMENTS



↑ Dusty plasma exists in space, such as in the rings around Saturn.

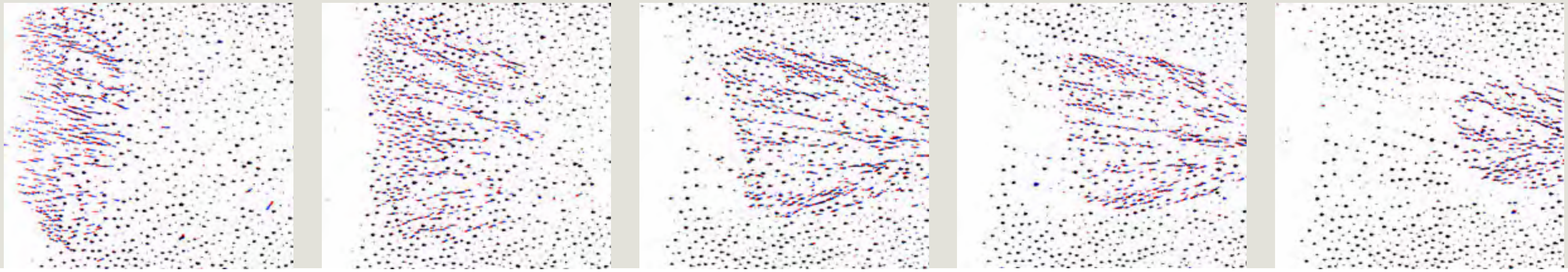
A LONG STORY – WITH LUCK

Gregor Morfill

Complete freedom of research, such as the Max Planck Society offers its directors, allows the scientists to choose whichever field of basic research promises the most interesting results. It was this privilege that made it possible for the theory group to make a radical change of direction. During the 1990s, the group's scientists began their own lab experiments on the ground as well as in space, complementing their theoretical work. In parallel, the group diversified with sophisticated methods from astrophysics being applied to many other fields in interdisciplinary collaborations.

Originally, Gregor Morfill was supposed to be a kind of "two-component adhesive" bringing together astrophysics and plasma physics – two areas that had been more or less separate until the early 1980s – not least because plasma physics is highly relevant for many astronomic processes and their measurement. And thus a group started to form, which would bring together ground-based activities in the field of space plasma research with space-based observatories for different wavelength disciplines.

←← The charged micro-particles are illuminated by a laser and then photographed or filmed so that the structures they form can later be analysed in detail.



↑ Inserting two sets of particles with different sizes into the plasma leads to the formation of lanes.

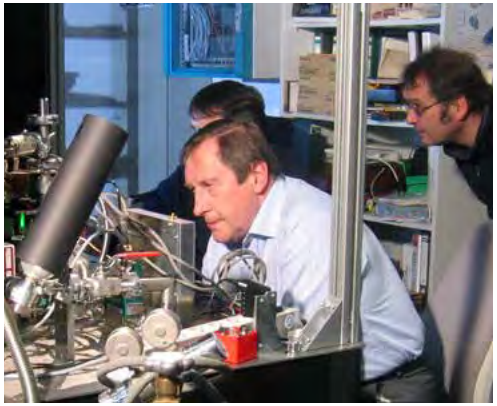
But then a tragedy changed the course of future research. On 1 November 1991, Christoph Goertz was shot and killed by a student in Iowa. The grief over losing a dear friend and colleague and the "Now we'll show them!" feeling that this engendered are what ultimately led to the discovery of plasma crystals.

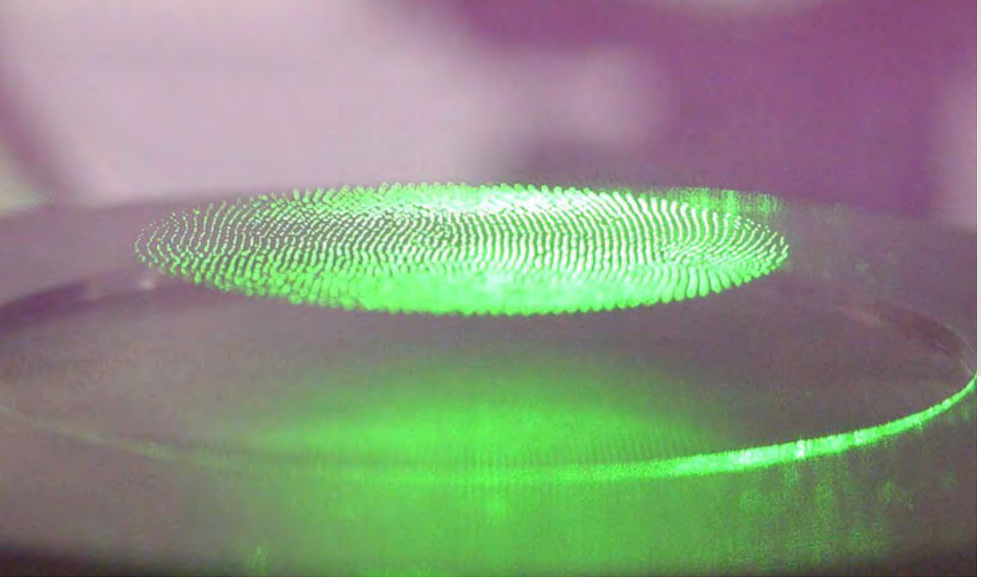
Gregor Morfill and Christoph Goertz had met while working on the interpretation of the structures in the rings around Saturn. To this day, the dusty plasma theory that they developed remains the standard interpretation of these phenomena. Then, at the end of the 1980s, discussions between theorists across the world suggested that plasma might show crystalline behaviour if micro-particles are added.

Theoretical considerations at the MPE confirmed this, revolutionizing the established paradigm: while plasma is the most disordered state of matter, the addition of micro-particles can lead to the formation of crystals, the most ordered state. Definitely an interesting topic, but one for which experimental proof was still lacking.

Experimental physicists did not show much interest in the discovery at the time, so the group decided to conduct experiments of its own. Its small budget was just enough to appoint a graduate student, who was able to use a vacuum chamber that happened to have become available in a DLR laboratory. One year later, they had not only managed to create the first argon plasma crystal, the theory had also been refined, showing that

↓ Gregor Morfill and his team study complex plasma to learn more about physical processes on the individual particle level.





← Processes normally known from fluid dynamics or solid state structures are visible to the naked eye in a dusty, complex plasma.

microgravity conditions were needed for large, three-dimensional crystals.

Again, chance and luck played their part. The international scientific journal *Nature* took up the topic and speculated that the plasma crystals discovered at MPE deserved a place aboard a Space Shuttle for further studies. This, in turn, led the Deutsche Agentur für Raumfahrtangelegenheiten (the precursor of the German Space Agency DLR) to invite Gregor Morfill to request permission to conduct experiments under microgravity conditions.

In the end, the Garching physicists carried out their experiments in parabolic flights and on sounding rockets, and several years later they became one of the first groups to conduct experiments on the International Space Station ISS. This led to many new discoveries of fundamental physical processes that can be studied by analysing the movement of individual particles and their interactions. Very little was known about such processes at an atomic level prior to the discovery of plasma crystals.

Chance and good fortune? As Nobel laureate Enrico Fermi observed, it’s all a question of actively doing something to encourage luck to come your way. A pioneering spirit and the openness for new ideas underpinned the positive atmosphere and good work in the theory group. The researchers moulded a new field of basic scientific research and were one of the main drivers in a global framework, something that provided unique opportunities to all group members. So the deciding factor in its long and changeable history was in the end not chance, but rather the dedicated work of an inspired and visionary team of researchers!

←↓ The plasma is created by an electrical discharge in a gas-filled cavity. If micro-particles are added, they “charge up” and form regular structures.

↓ This view shows a two-dimensional plasma crystal created in the MPE laboratories. The paper describing the first ever artificial plasma crystal has been cited more than 1000 times.

UNDER MICROGRAVITY CONDITIONS

Hubertus Thomas

In the late 1980s, the theory group around Gregor Morfill predicted that charged dust particles in plasma could form a regular crystalline structure. This idea emerged during his work on dusty plasma in space, for example, in the interstellar medium, the rings of Saturn or dusty tails of comets. To produce a plasma crystal, however, the theory assumed zero gravity, as the dust particles would otherwise sediment too quickly.

A proposal was therefore submitted to ESA to experiment with a plasma crystal on the so-called Columbus Precursor Flights – in preparation for the planned module on the International Space Station. While the review of the proposal was very positive, it was refused as there were no preliminary laboratory experiments. And this is why the theory group at MPE started their first experiments!

Everything had to be developed from scratch, from an appropriate vacuum chamber with windows to be able to observe the plasma and dust to the electrical system to produce and sustain plasma conditions. And then we had to search for appropriate "dust" particles – normal dust having shapes

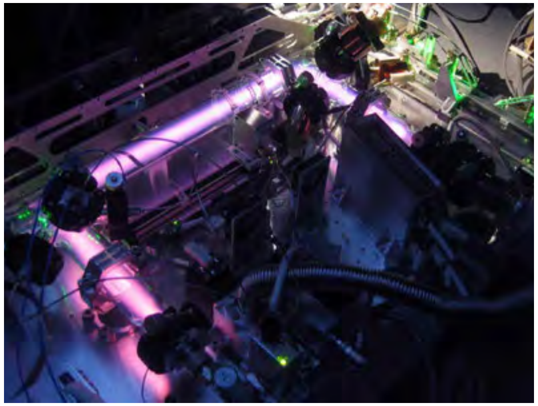
→ The specialised airbus ZERO-G flies extreme trajectories so that scientists from MPE and other institutes can perform experiments under microgravity conditions.

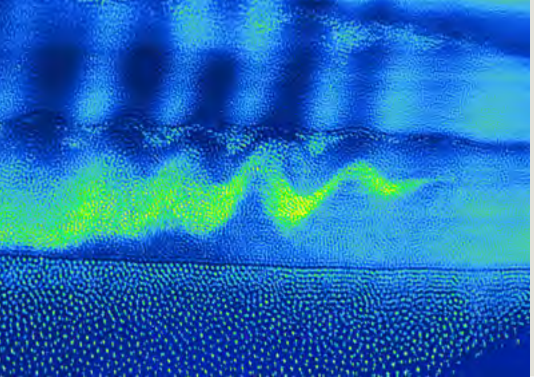
and sizes that are too irregular. Only for same-sized, globular particles could we expect similar charges leading to identical interactions between neighbouring particles and therefore regular structures. Finally in May 1993 all conditions were right: we saw the first 2D plasma crystal!

That this was possible even under gravitational conditions on Earth is due to the fact that the particles all have the same weight and carry the same electrical charge. They can thus be levitated in an electrical field, like in the famous Millikan experiment, resulting in a single-layer, 2D plasma crystal. For 3D structures, however, microgravity conditions are essential and therefore the next proposal for a space experiment, this time on-board the shuttle, was submitted to the German space agency DARA and was accepted. However, the experts at the German space agency advised us to first develop the experiment on parabola flights and sounding rockets; the experience gained on these flights proved crucial for the later success of the experiments on the ISS.

The laboratory plasma chamber was refined and became the workhorse for many more 2D experiments producing a wealth of interesting scientific results. In parallel, preparations for the microgravity-experiment progressed rapidly and in August 1996, the first parabola flight started with a plasma crystal chamber on board – with interesting physics results, but it played havoc with the experimenter's stomach! This was followed by the first sounding rocket experiment on TEXUS 35 in November 1996. Soon afterwards the Russian science minister Fortov saw the first achievements

↓ The next generation plasma crystal experiments are already under development to study anisotropic or multi-scale phenomena.





← Micro-particles of different sizes were injected into this plasma and separate in layers due to gravity. Inducing a flow then leads to the formation of waves which appear similar to waves on a beach.

↑ Micro-gravity experiments are essential for obtaining the precise measurements needed to study three-dimensional systems and stress-free processes.

on research rockets and immediately proposed a joint experiment on the Russian space station MIR. And while time was getting too short for this idea to be realised, the plasma crystal experiment PKE-Nefedov in 2001 was the first natural science project on board the international space station ISS.

In total, more than 30 campaigns have been carried out with PKE-Nefedov and from 2005 with PK-3 Plus, which is now permanently installed in the ISS module MIM-2. Complemented by the ground-based and flight experiments, many basic physical processes and in particular phase transitions have thus been investigated in great detail. The field of plasma crystal research has become a vibrant, new discipline for fundamental research as basic physical processes can be studied with unprecedented resolution and in slow motion, as if one could see atoms individually – the "atoms" in this case being the tiny micro-particles in the plasma.

↑ The cosmonauts operate the experiment on board the ISS, aided by the ground team. More than 30 experiment campaigns have already been completed.

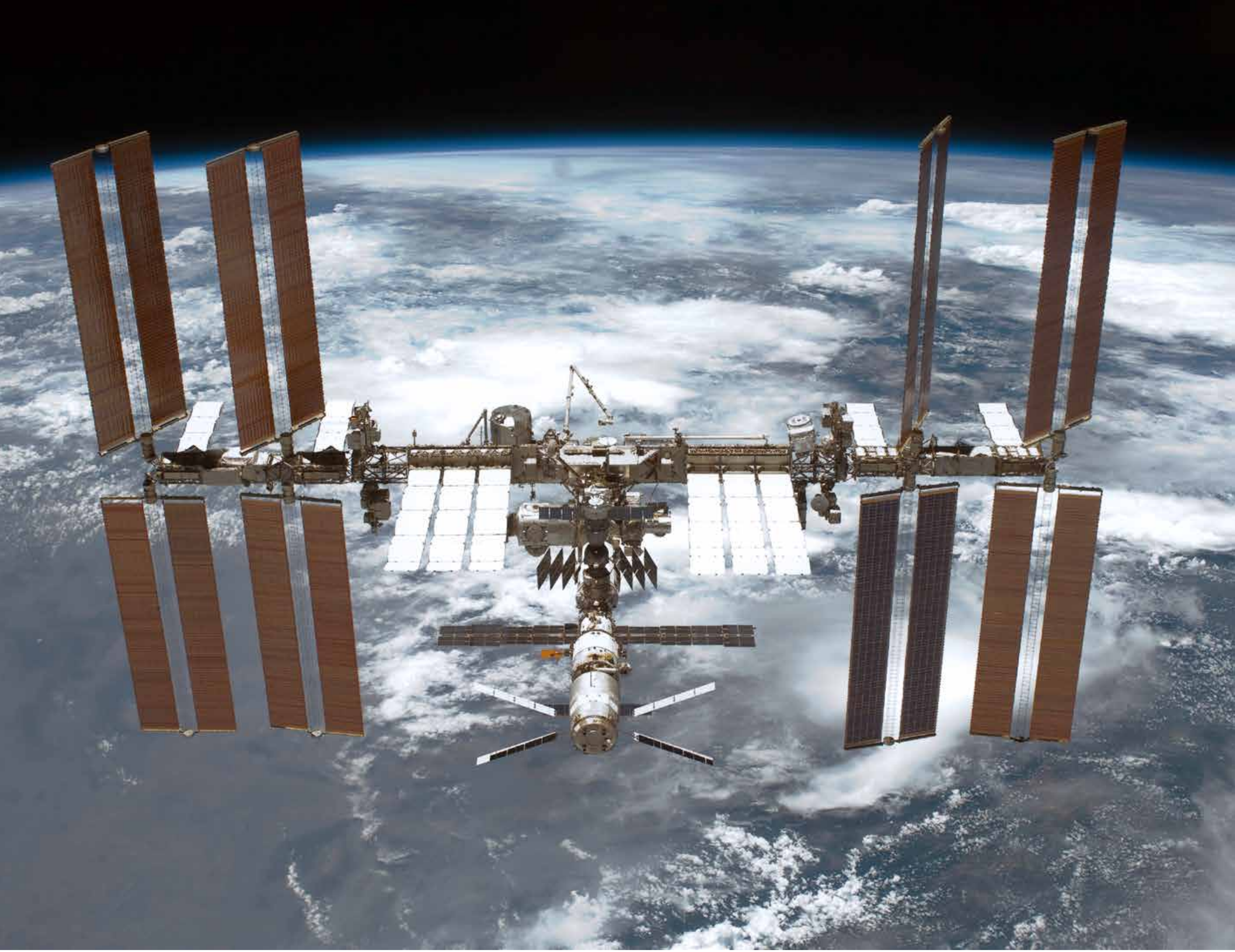
THE SERENDIPITOUS “BATURIN EFFECT”

Alexei Ivlev

To an outside observer it might sound anarchistic, but a deliberately self-organising structure is perfect for scientific research. It encourages open discussions with colleagues, an exchange of ideas across disciplines and borders, and links the realms of theory and experiment – particularly in space. The “complex plasma” field at MPE thrives on this freedom and the possibilities it offers.

> “Deliberately self-organising structure”

In April 1998, Gregor Morfill and Hubertus Thomas set out on an official trip to meet Vladimir Fortov, who was both Russia’s Deputy Prime Minister and Minister of Science and Technology at the time. The meeting, however, never happened because the Russian government had just disbanded. Nevertheless, it did not take long for Vladimir Fortov, who had meanwhile been appointed as an external scientific member of the Max Planck Society, to find another solution to facilitate the collaboration, which paved

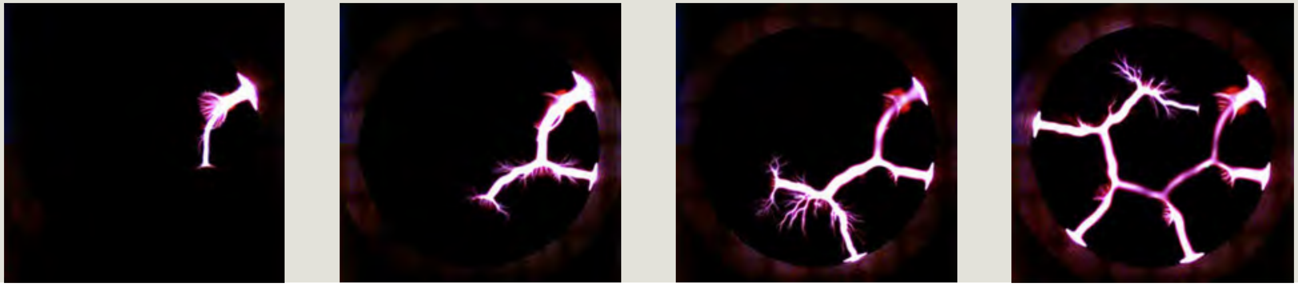


← The plasma crystal experiment PKE-Nefedov was the first natural science experiment on-board the International Space Station.

the way for an exceptionally productive link between theory and practice within the field of plasma research at MPE.

The first experiment to investigate complex plasma was carried out aboard the International Space Station with the PKE-Nefedov minilab in 2001. This triggered a close dialogue between theoreticians and experimental practitioners, and the scientists in Garching were able to exchange knowledge and ideas with over 30 cosmonauts and astronauts. It was now possible to speak directly with the people who actually carried out the experiments in space under zero-gravity conditions. The theory and the experiments both benefitted from this tremendously, as it broadened the horizons when viewed from the other perspective.

It's very difficult to imagine how a discovery such as that of the so-called "Baturin effect" could have happened otherwise. Fortunate mistakes in the experiment led to the discovery of fundamental, and indeed ground-breaking insights. Yuri Baturin was a well-respected politician at the top of Russian society. And he was set on fulfilling his dream of becoming a cosmonaut. Twice he went up into space, and once he carried out experiments for MPE. His breakthrough came when micro-particles accidentally entered the argon gas inside the plasma chamber before the gas had been ionized to form plasma. The dust particles floated weightlessly in the chamber, free to move in all directions. Within a few seconds, millions of particles clumped together. Evidently the particles had acquired a static electrical charge through friction which led to mutual attraction. But the process of formulating a theory to adequately explain this surprising observation took quite some time. Nowadays we consider it highly likely that the same effect could be responsible for the formation of planets or planetary systems.

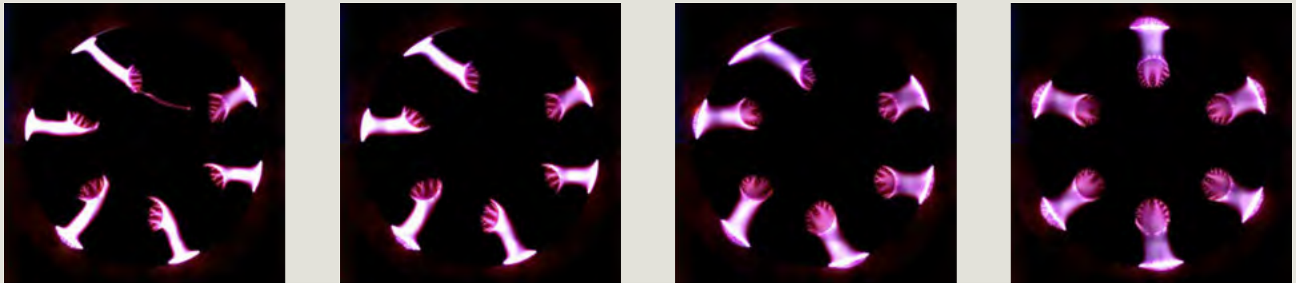


↑ Clinical studies have proved the effectiveness of plasma treatment for chronic wounds.

DESIGNER PLASMAS FOR MEDICINE

Julia Zimmermann

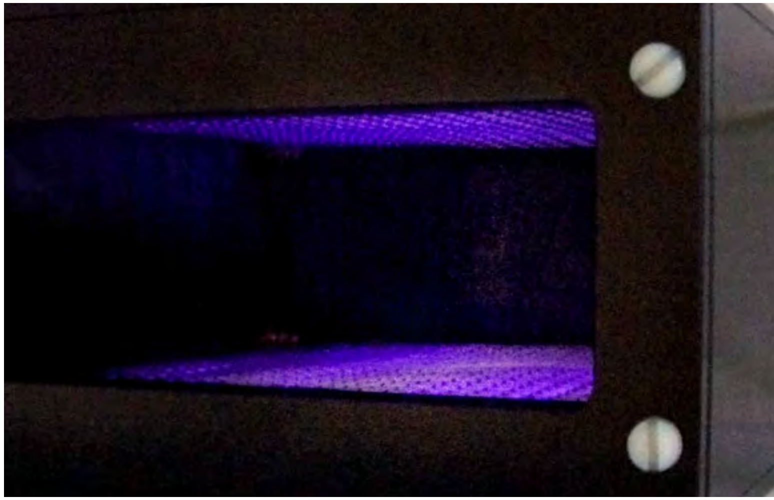
A case at the Klinikum Schwabing hospital in Munich received special attention in the medical community for the unconventional treatment that the patient received. He had fought with a genetic skin disorder for years, along with super infections that developed at the sites of the inflammation. He was forced to undergo repeated, arduous and drawn-out medical procedures to fight his illness – until he heard about the possibility of plasma treatment. After eleven applications of cold plasma to his lesions, the secondary bacterial and fungal infections accompanying the illness disappeared. But then, the patient was not seen again for a long period of time, causing hospital staff to fear the worst. A phone call, however, was answered by a lively, happy person – who was able to tell them, to his great delight, that all his symptoms had permanently vanished after receiving the plasma treatment.



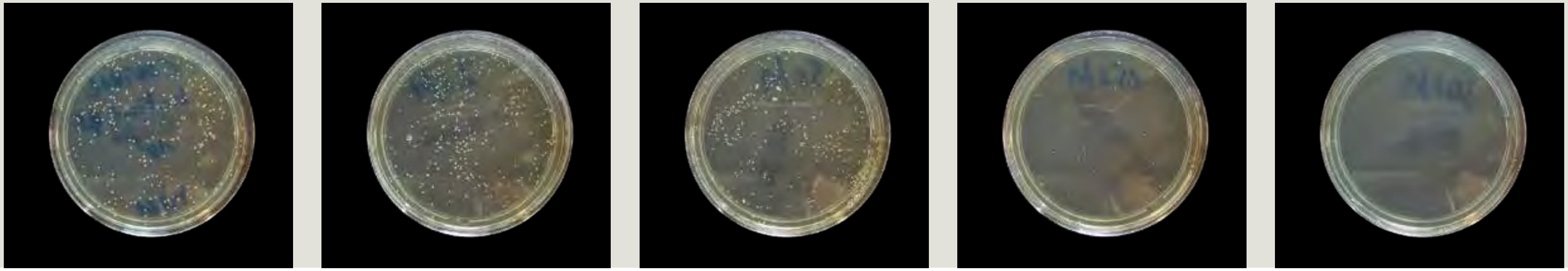
← The ignition of an atmospheric plasma, captured by a high-speed camera with 1000 frames per second.

This treatment method was developed at MPE as part of an interdisciplinary collaborative research project undertaken with numerous partners and with a focus on medical applications of cold atmospheric plasmas – partly ionized gases. Different plasma cocktails – this is how the scientists describe the plasma ingredients ranging from electrons and ions to reactive species and excited atoms or molecules – can now be put together to suit the type of wound being treated, with different combinations being used for chronic skin wounds or to treat skin graft wounds after transplantations. Bacteria, fungi and viruses are attacked and destroyed on any surface that can be reached with gas thereby enabling doctors to treat patients without having to prescribe antibiotics or other medicines, the use of which can often be problematic.

Since the start of the clinical study more than 3000 plasma treatments have been carried out. All studies indicate that this treatment holds no risks for the patient, with follow-up examinations showing that patients suffer no side-effects, no allergic reactions of any kind and no pain.



↑ Various prototype devices have been developed for hand disinfection.



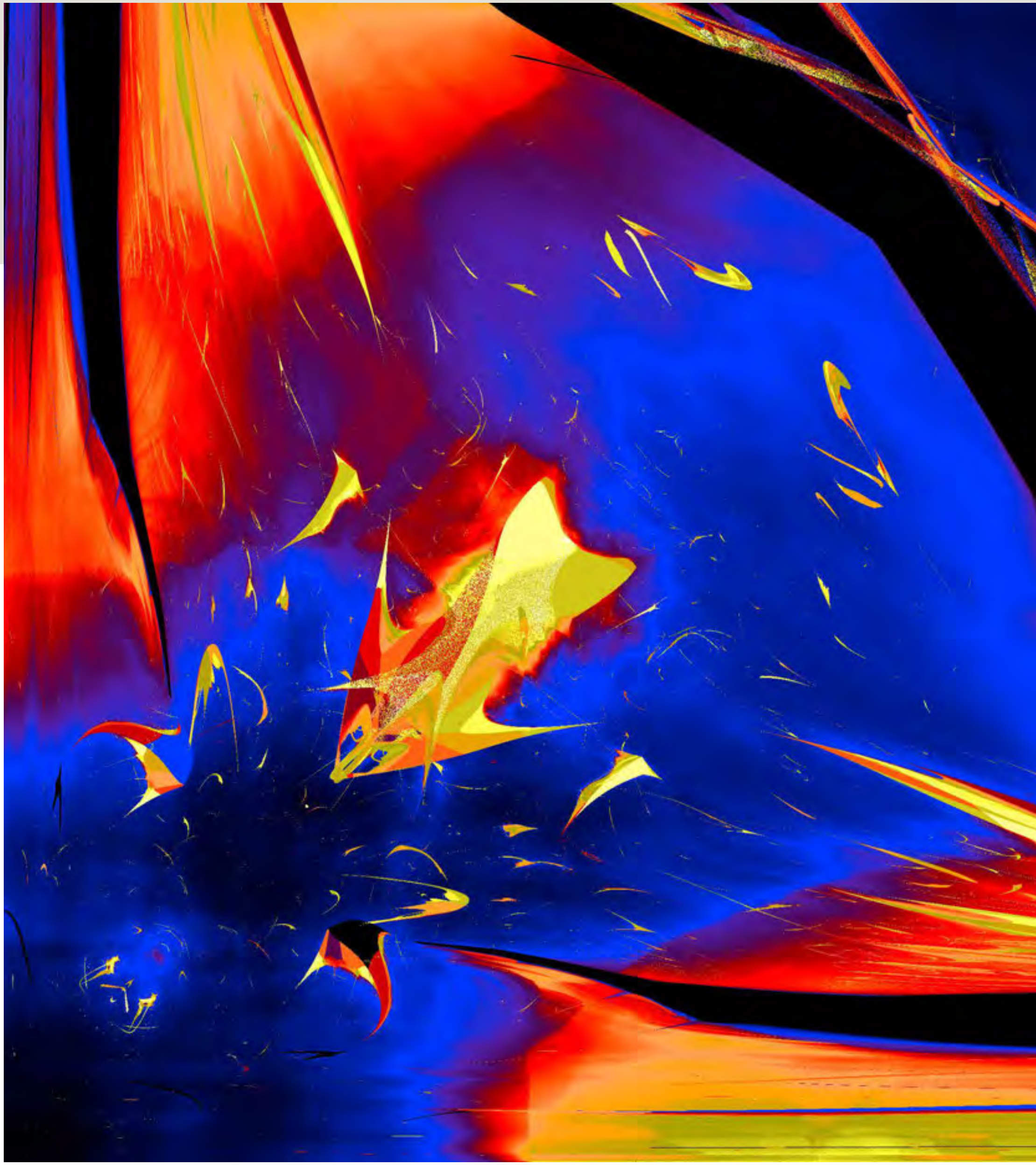
↑ The plasma treatment effectively kills all kinds of bacteria, even multi-resistant strains.

CHAOS IS EVERYWHERE

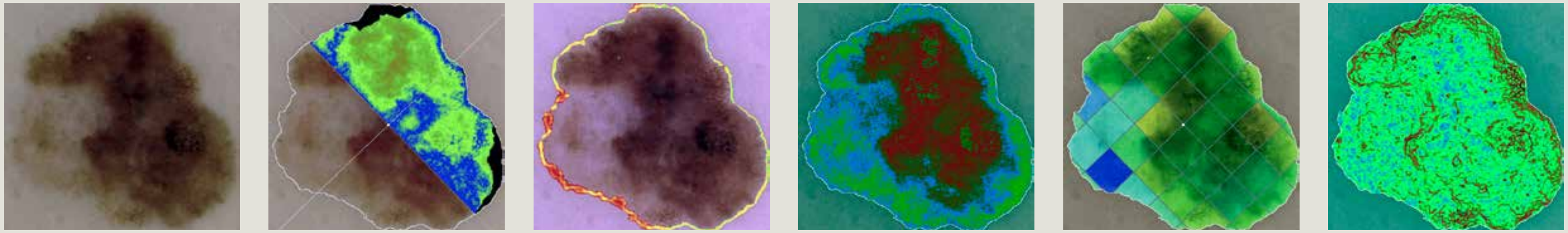
Wolfram Bunk

It was in 1989 when two proud fathers started talking on the sidelines of a junior football game, and an idea was born that would shape knowledge transfer at MPE. One was annoyed that conventional methods of statistical analysis offered no way of deducing the likelihood that patients would suffer a sudden cardiac arrest from evaluating their ECG data. In many cases, defibrillators could offer an effective way to prevent this common cause of death and thus save lives. But while an ECG can depict the complexity of the body's cardiovascular system, the quantitative diagnoses required were not readily available. It turned out that the other father, Gregor Morfill, had the key to this problem at his fingertips: his group at MPE was working on complexity analyses for astronomic measurements that could also be applied to other types of data. Two years later, Georg Schmidt of the Klinikum Rechts der Isar and Gregor Morfill founded an interdisciplinary research centre that uses chaos research methodology to analyse ECG data in more detail.

→ Complex systems may develop in a periodic, random, or chaotic way, depending on the interplay between their components. Mathematical modelling allows the study of the coupling complexity as a function of different parameters.



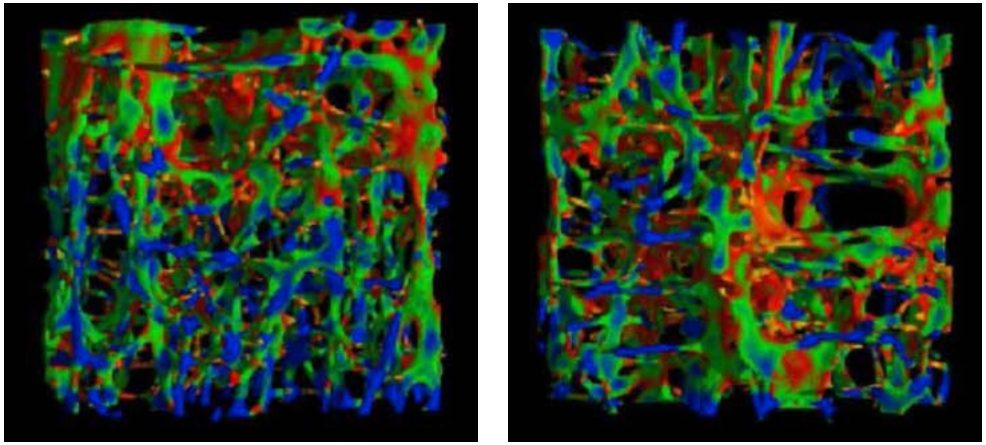
Over the years, this initial collaboration led to numerous further applications developed by MPE researchers and colleagues from other medical departments. Chaos not only exists in space – the human body also follows the rules of non-linear dynamics, both when it is healthy and when it is suffering from illnesses such as heart disease or malignant tumours. Fields of application include the early detection of skin cancer, quantitative assessment of tumours, bone structure analyses for evaluating the risk of osteoporosis, and obstetric diagnostics. The methodologies of complex systems support the development and testing of medicines; and once the process of knowledge transfer had been set in motion, it didn’t just stop at medical applications. It has also found useful applications in other areas, such as the engineering sciences and in particular in quality control and production.

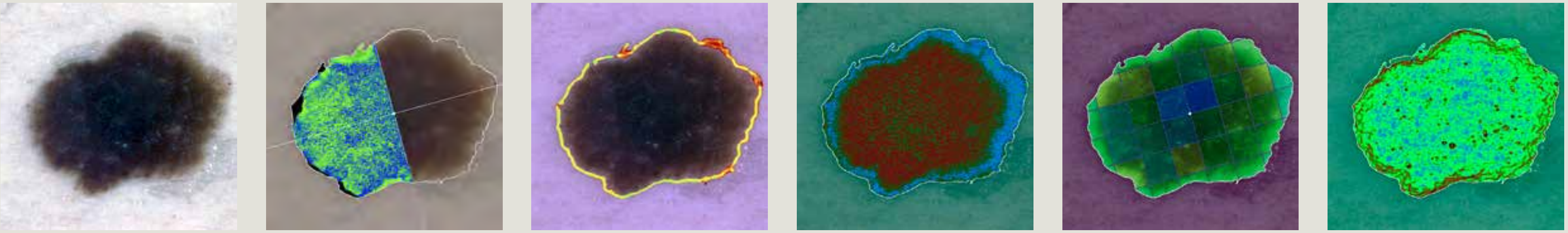


↑ A malignant melanoma (left page) differs from a benign lesion (right page) …

> “Analytical strategies developed for astrophysics”

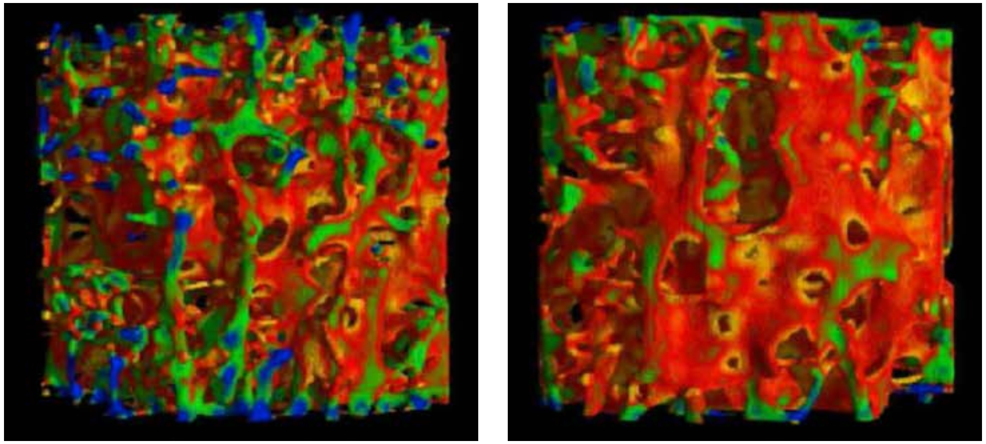
And all this just because the underlying techniques, such as the scaling index method (SIM), are rather abstract and universal. SIM was developed at MPE to quantitatively describe generic point distributions (e.g. astronomic measurements) in phase space (with the coordinates describing position or velocity information for astronomical objects). Methods from non-linear dynamics and information theory help researchers to understand the behaviour of the system as a whole. This means, for instance, to detect and study time-dependent variations in data series, or to automatically identify structures in images. The analytical strategies developed here for use in astrophysics can then be applied to all kinds of complex systems, together with innovative methods of data mining and data modelling.



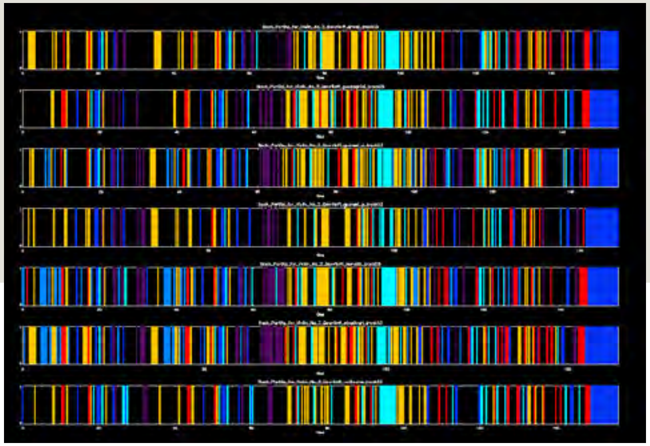


↑ … characterized by digital image analysis techniques.

This approach was presented at the European Space Agency's exhibition at the Hannover Trade Fair in a graphic and comprehensible manner and one of the many presentations showed a surprising audio-fingerprinting solution. The application compares snippets of music with sequences lasting only fractions of a second – shorter than the melody, but the key and instrumentation are recognizable. For each fragment, the different composers and interpreters can then be quickly and precisely identified on a computer. But the technique can not only differentiate between characteristics of different composers and interpreters, it can even identify the maker of an instrument if a musician plays the same piece of music on several different violins.



← Osteoporosis can be diagnosed by the assessment of the trabecular bone micro-architecture.



↑ The characteristic sound patterns of different violins provide an acoustic fingerprint for each instrument.

Methods from the field of ordinal symbolic dynamics examine time series in complex, coupled systems as well. Promising areas of knowledge transfer include speech recognition or the identification of audio plagiarism. As soon as similar patterns can be identified in a time series, even extremely short sound sequences can be attributed to reference material with a high degree of certainty.

STUDENTS

Young researchers → 128

↑ Summer and winter outings are a great way to get to know each other better and to learn something about places close to Munich, such as the Galileo Test Facility GATE in Berchtesgaden, the Tegernsee region, or the Benediktbeuern monastery. The first group of IMPRS students made an excursion to the Wendelstein-Observatory in Bayrischzell in 2001 (leftmost image).

←← Excursion to the highest meteorological station in Germany and the MPE "Meßzahn" on the Zugspitze/Garmisch.

YOUNG RESEARCHERS

Joachim Trümper, Werner Becker

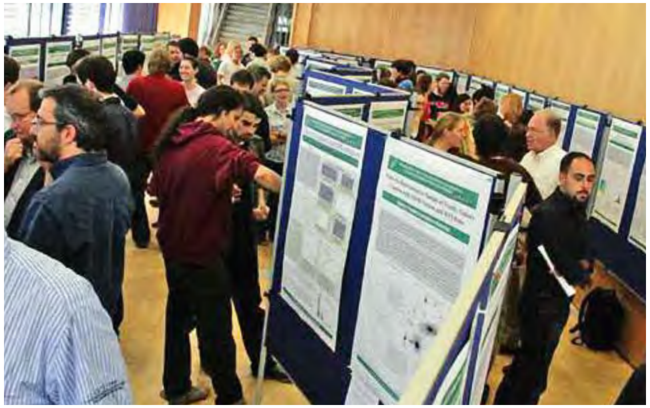
When the Max Planck Society decided to strengthen its ties to the local universities by means of joint graduate programmes, this idea fell on fertile ground at MPE. It was a great way of promoting young researchers, not only by offering projects for all astronomical interests but also by complementary lecture programmes and the chance to discuss the latest astrophysics results with leading scientists. The initial reaction of the other astronomical institutes and in particular the University of Munich's observatory, however, was not enthusiastic.

An invitation to the "Freisinger Hof" restaurant in Munich did the trick. The main concern of the university's scientists was that the lectures would become their task by default. This problem could however be solved by organising block lectures at the different institutes with mainly local speakers. And once the university had been convinced to participate, the Max Planck Institute for Astrophysics and the European Southern Observatory

came on board as well. Taking all four institutions together, there are only few places world-wide that can compete with the breadth and level of research offered at the International Max-Planck Research School (IMPRS) on Astrophysics, which officially started in 2001 as one of the first schools in the Max Planck Society.

Posters were sent out to astronomy institutes all around the world to attract the best students – with the positive side effect of increasing the visibility of the participating institutes even in remote corners of the world. In 2003, an astronomy conference took place in Mauritius and one of the excursions went to the Mauritius Radio Telescope in the middle of the Bras d'eau national park. Imagine the surprise of the scientists when the only poster on the observatory's notice board was the IMPRS poster from Garching!

As a result of this wide-spread promotion, the IMPRS students come from many different countries and sometimes bring their own, unfamiliar customs with them. Some bewilderment was caused when, during one of the all-day IMPRS introductory events, a Chinese student was found sleeping on a table in an unused seminar room, with his bag as a pillow and shoes neatly arranged under the table – taking an afternoon nap being much more common in Asia. Such cultural differences, however, are easily



↑ After ten years, the IMPRS was evaluated, with all current students presenting their work. The unanimous decision was: the school must go on!

> **"Sleeping on a table in an unused seminar room"**

reconciled and more than offset by the unique benefits offered by being part of such an international group.

After graduation, most of the students either pursue their careers at other leading research institutes around the world or go back to their home countries to take up academic positions, strengthening the international network. Some are already on track for professorships, and all contribute to the success of astrophysics as evidenced by more than 2000 scientific papers published by IMPRS students so far.