Extract from the book "Astronomy's Limitless Journey: A Guide to Understanding the Universe" by Günther Hasinger

Chapter 8: Cosmic Monsters

The resolution of the X-ray background

The American astrophysicist Riccardo Giacconi can look back on a fascinating career as a scientist and science organizer. In 2002 he was awarded the Nobel Prize in Physics "*for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources*". I had the pleasure to work with him intensively for more than a decade, and to learn from him. Riccardo was born in Genoa in 1931 and studied physics at the University of Milano. He earned a doctorate there and immediately became assistant professor of physics. At the age of 25, he went to the U.S., first at the University of Indiana in Bloomington and later at Princeton University. His career as a pioneer of space exploration began when he received an offer from American Science & Engineering Inc. (AS&E) in Cambridge, Massachusetts. This company was founded by Bruno Rossi to perform research and development for the government. When Giacconi joined the company in 1959, AS&E had 28 employees. Right after the Sputnik shock he was charged to build up a space program for the company, with great freedom for research. Judged from Giacconi's autobiography,[1] the years 1959–1962 were among the most productive periods of his life. He "*participated in classified research, a total of 19 rocket payloads, six satellite payloads, an entire satellite and an aircraft payload, and four rocket payloads for geophysical research.*" In these two and a half years, Giacconi's group in the company grew from the original three to more than 70 employees.

The year 1960 saw the beginnings of X-ray astronomy. At a party at his house the CEO of AS&E, Bruno Rossi, reported about discussions in the National Academy of Sciences on the potentials of X-ray astronomy and suggested that the company should invest in this area. Immediately thereafter Giacconi put together a report on the theoretical and experimental possibilities of X-ray astronomy.[2] X-rays are absorbed by the Earth's atmosphere, so that instruments for their observation must be brought into space. Already in 1949, U.S. physicists around Herbert Friedman of the Naval Research Laboratory had launched a converted V-2 rocket from the Second World War, and discovered X-ray radiation from the Sun, the brightest X-ray source in our vicinity. In their first estimate, Giacconi and his colleagues came to the conclusion that the then-existing instruments would never be able to observe the X-ray emission from other stars radiating as bright as the Sun, due to their much greater distance. The same report also discussed supernova remnants and other peculiar celestial sources, but the uncertainties regarding their possible X-ray emission were huge. They therefore came to the conclusion that solely the observation of the Moon, whose surface reflects the solar X-rays, would offer a certain chance for discoveries. Around the same time NASA was planning the Apollo program, and Giacconi convinced the government agencies to provide funds for the development of a rocket payload, which was 50 to 100 times more sensitive than any instruments used until then, to observe the fluorescence radiation of the Moon. They hoped to study the chemical composition on the lunar surface, long before an astronaut would set foot on the Moon.

On June 12, 1962 everything was finally ready. Two previous rocket launches had unfortunately been unsuccessful. But this time the rocket rose successfully and outside the Earth's atmosphere performed a scan across the whole sky for about 5 minutes. The highly sensitive detectors worked wonderfully and recorded the intensity from the different directions in the sky. The result was fundamental in two respects.[3] First the scientists around Giacconi discovered the signal of a very strong X-ray source in the sky, much stronger than anything they had expected in their previous estimates. Although the signal was roughly from the direction of the Moon, it was almost 30 degrees away from it and therefore clearly not connected with the Earth’s companion. Since the source is located in the constellation Scorpius, it got the name Scorpius X-1 (or abbreviated Sco X-1), the first X-ray source in this constellation. Years later, this source could be identified by ever more precise measurements as an X-ray binary star system, in which a neutron star accretes matter from a normal companion star. In contrast to ‘normal’ stars like the Sun, in which the

X-ray light makes up only about one millionth of the total radiated energy, Sco X-1 is an X-star, which behaves vice versa; it emits the majority of its radiation in X-ray light. Over the years, many other bright X-ray stars were found in other constellations, which were then named accordingly Cygnus X-1, Cygnus X-2, Hercules X-1, etc.. Many years later I had a certain share to better understand this class of X-ray binary star systems, which is still my highest-cited paper. A perhaps even bigger surprise, however, was the discovery of a constant background radiation across the whole sky, measured by the detectors of the first successful rocket flight. Taken together, this diffuse radiation is about as bright as Sco X-1, the brightest discrete source in the sky. If we had X-ray eyes (and could be outside the Earth's atmosphere), we would need no reading light at night, because the sky is shining brightly enough. The diffuse X-ray glow was the first extragalactic background radiation discovered – a few years before the microwave background radiation discussed in chapter 3.

Together with Bruno Rossi, Giacconi also developed the concept of an imaging X-ray telescope in 1960, on the basis of which all later X-ray optics operated in space. He took advantage of the ideas of the German physicist Hans Wolter, who originally wanted to use these optics for X-ray microscopy already in 1954. In the title of the paper published in a geophysical scientific journal, the word 'telescope' is interestingly still set in quotation marks. In 1963, Giacconi along with Herb Gursky created a roadmap for the future development of X-ray astronomy. It began with additional rocket experiments, followed by satellites. First simple, non-imaging X-ray detectors should be used, then one with a first imaging X-ray telescope, and finally a large X-ray satellite with a 1.2 meter diameter mirror system, which would be able to resolve the X-ray background into individual discrete sources. Giacconi and Gursky originally thought, this plan could be realized within five years, but that was far too optimistic. The process took until the end of the millennium, but all components of the original plan were eventually realized, and we still take precious observations with the *Chandra* observatory.

The first satellite developed under Giacconi's leadership was *Uhuru*. It was launched in December 1970 from a floating platform off the coast of Kenya. The name *Uhuru* means 'freedom' in Swahili and was chosen in honor of the people of Kenya because the launch fell exactly on the seventh anniversary of the independence of this African country. *Uhuru* discovered about 400 X-ray sources in the entire sky, most of them compact X-ray binary systems in the plane of the Milky Way, but also a number of extragalactic sources. The second satellite built under the direction of Riccardo Giacconi was renamed '*Einstein Observatory*', following its successful launch in November 1978. It carried the first non-solar imaging X-ray telescope with four nested mirror shells in the shape prescribed by Hans Wolter: a paraboloid connected to a hyperboloid. The largest shell had a diameter of 58 cm and the telescope had a resolution of about 5 arc seconds. The mission was completed in April 1981. Giacconi's biggest dream was realized only in July 1999. As one of the NASA 'Great Observatories' *Chandra* is now one of the main workhorses of X-ray astronomy, together with ESA's *XMM-Newton* observatory. Chandra, with an image quality of 0.5 arc seconds, is the highest angular resolution X-ray telescope ever built and flown. Because no major new high-resolution X-ray telescope is planned for the foreseeable future, Chandra will hold this honor for decades to come.

In parallel, Joachim Trümper began to build X-ray astronomy in Germany. Like several other international high-energy astrophysics, he had started his career with the study of cosmic rays. Around 1970 he began to work in the new field of X-ray astronomy, in particular on the physics of neutron stars, one of the fields in which he had and still has great achievements. After he moved from the University of Kiel to the University of Tübingen in the early seventies, he built an instrumentation and balloon flight program in X-ray astronomy there. In 1975 Joachim Trümper was appointed as a member of the Max-Planck Society, where he took up the position of director at the Max-Planck-Institute for extraterrestrial Physics (MPE) in Garching. The most important result of the balloon payload HEXE (High-Energy X-ray Experiment), jointly developed by the MPE and the University of Tübingen, was the discovery of a cyclotron line in the spectrum of the bright X-ray pulsar Hercules X-1, allowing the first direct measurement of the gigantic magnetic field on the surface of a neutron. The magnetic field of Her X-1 is about $5 \cdot 10^{12}$ Gauss, approximately five quadrillion times higher than the Earth's magnetic field.[4] Already in 1972, Trümper began to investigate observation techniques with the aid of imaging X-ray optics together with his colleagues in Tübingen. In 1974 he submitted the proposal for a national X-ray satellite to the German Federal Ministry of Research, which years later turned into *ROSAT*. Together with the company Carl Zeiss in Oberkochen his team developed small 32 cm diameter Wolter telescopes, which were launched on Skylark rockets, together with very sensitive imaging proportional counters developed at MPE. The first of three successful rocket flights was launched in spring 1979 from the Australian base Woomera and took the first X-ray color images of a cosmic X-ray source (the supernova remnant Puppis A), a few weeks before the *NASA Einstein Observatory* began its operations.

At this point, I need to weave in some of my own biography. My enthusiasm for physics and astrophysics actually came only at the end of high school and while studying at Munich University. In school, I was fascinated by books about modern science, for example Werner Heisenberg's philosophical notes '*Schritte über Grenzen*' (Steps Beyond Boundaries)[5], and I devoured Hoimar von Ditfurth's evolutionary book '*Im Anfang war der Wasserstoff*' (In the Beginning was Hydrogen)[6], by the way, together with my current wife Barbara. But the decision to study physics and later even astronomy, was the result of many detours, among others my career as a rock musician in the band *Saffran*. I found my real passion for astronomy through Rudolf Kippenhahn's astronomical lectures, which he published shortly afterwards under the title '*One Hundred Billion Suns: Birth, Life and Death of the Stars*'.[7] He held these excellent lectures at the Ludwig-Maximilians-University for students of all faculties and always had a full lecture hall. They were very popular, because Kippenhahn has the gift to explain rather complicated subjects in a way easy to understand. You could even bring your girlfriend into the lecture. In the summer of 1978 I had the good fortune to obtain my first own astronomical observing experience at the University Observatory in Munich–Bogenhausen. In every clear night throughout the whole summer I took photographic spectra of a bright Nova that had just erupted in the constellation Cygnus. As expected, the Nova Cygni 1978 became progressively weaker in the weeks and months after the explosion, so I had to upgrade the acquisition and guiding system of the telescope to continue to observe this phenomenon. The whole thing came abruptly to an end, when the Oktoberfest illuminated the sky over Munich so brightly that you could not see stars any more. In winter 1978/79 I heard Joachim Trümper's fascinating lectures on X-ray astronomy. I still remember one afternoon in the Schellingstrasse in which he challenged us with the remark that perhaps one of us would be able to solve the mystery of the asymmetric pulses of the rapidly rotating neutron star in the Crab Nebula.

Towards the end of the semester I went to him and asked for advice in choosing a diploma thesis. He said, "*why don't you just come with me*", ushered me in his car and drove me out to the Max-Planck-Institute for extraterrestrial Physics (MPE) in Garching, where I have spent a substantial fraction of my scientific career since then. In the spring of 1979, while a large part of the MPE team participated in the aforementioned rocket launch campaign in Australia, I started my diploma thesis on the scattering of X-rays on polished surfaces. This work was a preparation for the *ROSAT* mission, which required extremely well polished X-ray mirrors. The Wolter telescopes are irradiated by X-rays at very slant angles and reflected twice. Since X-rays have a very short wavelength, they see the tiniest bumps on the mirror surface like gigantic mountains, unlike the situation with the visible light, which has typically a 1000 times longer wavelength. Therefore, X-ray mirrors must be so exquisitely well polished that the average amplitude of the surface irregularities is only a few atomic layers. At that time this was still an unsolved problem. During my diploma thesis the company Carl Zeiss in collaboration with MPE succeeded to develop ever more accurately polished mirror samples. We measured the surface roughness of these samples at the vacuum X-ray test facilities of MPE and communicated the results directly back to the polishing specialists at Zeiss. This work later led to the entry of the *ROSAT* mirrors into the Guinness Book of World Records as the smoothest surfaces in the world.

In the meantime the scientists of the X-ray groups in Garching and Tübingen, who had originally discovered the cyclotron line in Hercules X-1, had carried out several more successful balloon flights and prepared a new, much larger balloon gondola, which was supposed to carry three HEXE detectors and a new high resolution germanium semiconductor detector. At that time the brand new CCD (Charge-Coupled Device) detectors, which nowadays are built into every digital camera and smartphone, became commercially available for the first time. As part of my dissertation thesis project I had the task to develop a separate CCD star camera for the balloon gondola. It was a lot of fun for me to design the camera and solder together its electronics and later program its chips. In parallel I was responsible for the maintenance and calibration of the semiconductor detector, which had to be continuously cooled with liquid nitrogen. This work culminated in two balloon campaigns in the years 1981 to Palestine, Texas and 1982 to Uberaba, Brazil. The high altitude research balloons can carry payloads of more than one metric ton into the stratosphere, the uppermost layer of the Earth atmosphere at 40 kilometers altitude. On the ground a small part of the balloon is filled with helium (sometimes also with hydrogen, but this is very dangerous). While the balloon first rises like a huge elongated sausage, it puffs up as it reaches the thinner layers of the atmosphere until it floats in the stratosphere like a ball of about 100 meters in diameter. There it would be blown away at high speed by the winds of the jet stream. Twice a year, however, the western wind direction turns around for a short time. These so-called 'turnarounds' see a pilgrimage of high-altitude balloon researchers from all nations, who try to bring their payloads into the air. Since the average wind speeds during the turnarounds are much lower, the high-altitude research balloons with some luck can stay several days in the air and send data. However, during the launch in the low layers of the atmosphere absolutely no wind is allowed, otherwise the extremely thin balloon skin is in danger of being damaged during the release. Because of the always unpredictable vagaries of the weather and the material defects occurring quite frequently at that time, balloon flying was a very risky business. Of the two flights, in which I was involved, the first was a great success, but the second had had to be aborted after a few hours because of a balloon failure. Nevertheless, we obtained nice data of the Crab pulsar, and as predicted by Joachim Trümper, I could indeed address the challenge of its asymmetric pulse structure in my PhD thesis.

In the meantime, the German Federal Research Ministry had approved the *ROSAT* mission, and when I was finished with my PhD thesis, I was immediately hired into the *ROSAT* team. There I had several tasks. On one hand, because of my experience with polished surfaces from the diploma thesis, I was involved in the calibration of the *ROSAT* mirror system, but could also participate in the calibration of the *ROSAT* focal plane detectors. The imaging proportional counters (PSPC: Position Sensitive Proportional Counter), which a team around our colleague Elmar Pfeffermann had developed, belonged to the outstanding technological achievements of their time and contributed a major fraction to the later success of the *ROSAT* mission. Even today, a flight–spare model of such a detector is used in the large MPE X-ray vacuum test facility *PANTER* in Munich-Neuried. For months, calibration measurements of the mirrors and the detectors were performed at this test facility in the years before the *ROSAT* launch. My small group had the task to immediately analyze the data tapes that were brought in the evenings by drivers from Neuried to Garching, if possible still in the same night, to give the calibration team a rough feedback for the measurements to be performed on the next day.

Maybe because of my experience with the star camera of the HEXE balloon gondola, I also was charged with the scientific responsibility for the attitude measurement and control system of the *ROSAT* mission. We accompanied the calibration measurements of the star sensors and the so-called 'hardware-in-the-loop' test at the company MBB in Ottobrunn near Munich, where a realistic end-to-end simulation of the whole satellite attitude control system took place. These activities should later turn out to be particularly important, as one of the four gyroscopes on *ROSAT* failed shortly after the beginning of the mission, which put the function of the entire mission in danger. In cooperation between industry, scientists and the ground control system GSOC in Oberpfaffenhofen, we had to reprogram the gyro control of the satellite into a magnetic compass control, practically like in an open heart surgery. The concept of magnetic field control for three axes stabilized satellites, which was brand new at that time, was able to prolong the active life of *ROSAT* for many years, even after several other gyro failures, and has now become standard in a number of satellite systems.

An extremely important activity, that later contributed to the immediate understanding and the rapid scientific utilization of the ROSAT data, was a realistic computer simulation of the mission. Starting with idealized assumptions first, but later fed with more and more detailed information from the calibration of the instruments, we simulated observations of the *ROSAT* mission, as good as possible. Every single X-ray photon was artificially created in the sky and then tracked on its way through the mirror system and the detector. Over time, these simulations became more and more realistic, we included point-like and extended objects in the sky, different spectral models and even the temporal variability of the X-ray emission. Also, the background radiation, the extragalactic cosmic ray radiation, solar scattered radiation and the intrinsic background of the detector were simulated as realistically as possible. In this way, we had access to fairly realistic data long before the real mission, and were even able to modify and improve the flight software for the satellite.

One of the concerns was the support structure for the PSPC cameras. These gas proportional counters had a very thin entrance window for the X-ray photons. The overpressure of the counter gas would cause the window to burst, if it were not protected by a highly complicated and finely chiselled network of wires. However, this network is casting a shadow on each X-ray image that the satellite receives. At the beginning we were still hoping that the inherent jitter of the *ROSAT* attitude control system would wash out these shadows. However, when we fed the results of the first realistic attitude control tests into our simulation program, it soon became clear that the satellite orientation was way too stable. This shortly before the completion of the mission preparation, it was not easy to explain to the engineers in industry, especially the main contractor Dornier System in Friedrichshafen, as well as the funding agency in Bonn, that the system had been constructed too well and thus we need to include an artificial dithering motion in the satellite flight software. I then convinced them with the argument that even the human eye has a blind spot, which is compensated by the constant movement of the eyeball and the corresponding data analysis in the brain. This so-called 'wobble mode' in which the viewing direction of the satellite was wandering back and forward on a time scale of a few minutes, later contributed significantly to the high quality of the *ROSAT* observations and was even implemented in the NASA *Chandra* observatory in an expanded form.

In 1985 Joachim Trümper assembled an international team of scientists in Garching, who were all interested in very long and sensitive surveys of the X-ray background radiation. Riccardo Giacconi, who in the meantime controlled the fate of the *Hubble Space Telescope* at the Space Telescope Science Institute in Baltimore, had brought along his young colleague Richard Burg. The two had experience with the deep *Einstein* surveys and proposed to focus on a sky area, which we later called the 'Lockman Hole'. This area, where the density of the disturbing foreground absorption of the Milky Way shows an absolute minimum, and which therefore represents an ideal window for the extragalactic Universe, had just been discovered by the U.S. radio astronomer Jay Lockman and his colleagues. Gianni Zamorani from the Astronomical Observatory in Bologna had already gained a lot of experience with observations of faint quasars in visible light. Maarten Schmidt from the California Institute of Technology, the discoverer of quasars, had previously calculated detailed predictions of how many X-ray sources should be detected in deep surveys with *ROSAT*. He planned the optical follow-up observations, first with the big 5–meter mirror on Mount Palomar and later with the 10-meter Keck telescopes in Hawaii.

For more than one decade, this team met every six months for a few days in Garching and worked on the preparation and implementation of the deep *ROSAT* surveys. Already during the first meeting I as a young bung was entrusted with the responsibility for the 'Deep Survey' project. It was a challenge, but also a great opportunity for me. We dealt with the astrophysical backgrounds, detailed simulations of the observations, the tricks of the data analysis and in particular their statistical and systematic effects, the preparation and implementation of the optical observation campaigns, writing applications for the *ROSAT* observing time and later with the analysis of the first results. I still remember many of our meetings well. Riccardo and Maarten were very constructive, but usually also very critical. Sometimes they were of opposing opinions, and we argued for hours with great verve. But often they also disagreed with my proposals for the observational strategy or the data analysis methods. In these cases I had to spend most of the night with new simulations, in order to convince them the next morning. Riccardo once said that the *ROSAT* mission was far better prepared and the data analysis better understood before the launch than was the case for the *Einstein* mission even years after its completion. I regarded this as a great compliment. Anyway, the highlight of these meetings was usually a sumptuous dinner at the Augustiner Bräu in Munich, where Riccardo particularly appreciated the excellent quality of the Apfelstrudel.

The Lockman Hole actually covers several degrees on the sky. At first we had to determine the optimal location for our survey. At some point Maarten Schmidt realized that the field is very close to one of the bright stars of the Big Dipper, which we were able to avoid at the last minute before the start of the observations. We started an optical survey of the field well before the *ROSAT* launch. Later, many other groups have selected this area for deep surveys in other wavelength regions, such that the Lockman Hole became one of the best-studied extragalactic fields on the sky.

I have already reported about the dramatic night of the Challenger catastrophe, which delayed the start of the *ROSAT* mission for several years. After intense preparations and a long waiting time, *ROSAT* was finally launched successfully on June 1st, 1990, on a Delta rocket from Cape Canaveral in Florida. A particularly exciting moment was the important ‘First Light’, when the PSPC detector was first switched on after the telescope opened its eyes. On June 16 a large crowd from the *ROSAT* team and some guests gathered at the German Space Operations GSOC in Oberpfaffenhofen. Of course, we were all curious if the X-rays would really be imaged correctly in the telescope. I myself was particularly nervous because the wobble mode was tried for the first time in real life. We picked a date on which we had a direct contact with the satellite from a ground station in Australia and we could target the Large Magellanic Cloud, where a few years earlier the supernova 1987A had gone off. Everyone held their breath as the first single X-ray photons appeared on the screen. As the image of the Magellanic Cloud gradually assumed contours, cheers and standing ovations broke out. Embarrassingly, however, I had made a mistake in the initial programming of the attitude software – either a wrong sign or a reversed trigonometric function. Anyway, the wobble mode of the satellite was not properly corrected out, but on the contrary was amplified by the software error, such that all detected X-ray sources were initially drawn out into elongated traces on the sky. But this did not detract from the general joy at the successful opening of *ROSATs* eyes.

The first weeks and months of the mission were very dramatic and exhausting, but the intense preparation of the entire team was a great help for us in this phase. Together with my colleague Peter Predehl we had developed a first preliminary data analysis system from the calibration and simulation software, which we called 'Trampelpfad' (trodden trail), through which we were able to supply the world-wide researchers with *ROSAT* data in the first months of the mission. As one of the first spectacular *ROSAT* observations, we were able to repeat Giacconi's original experiment 28 years after the first rocket flight and observe the Moon in X-rays. The X-ray image of the Moon (Figure 46)[8] is, among other reasons fascinating because the dark side of the Moon really casts a shadow on the diffuse X-rays behind it. With this picture, it became clear that *ROSAT* was perfectly suited for the study of diffuse X-ray radiation because of its extremely low intrinsic background signal.

In the first half year of its mission *ROSAT* performed the first all-sky survey with an imaging by X-ray telescope. Comparing the ROSAT map of the X-ray sky (

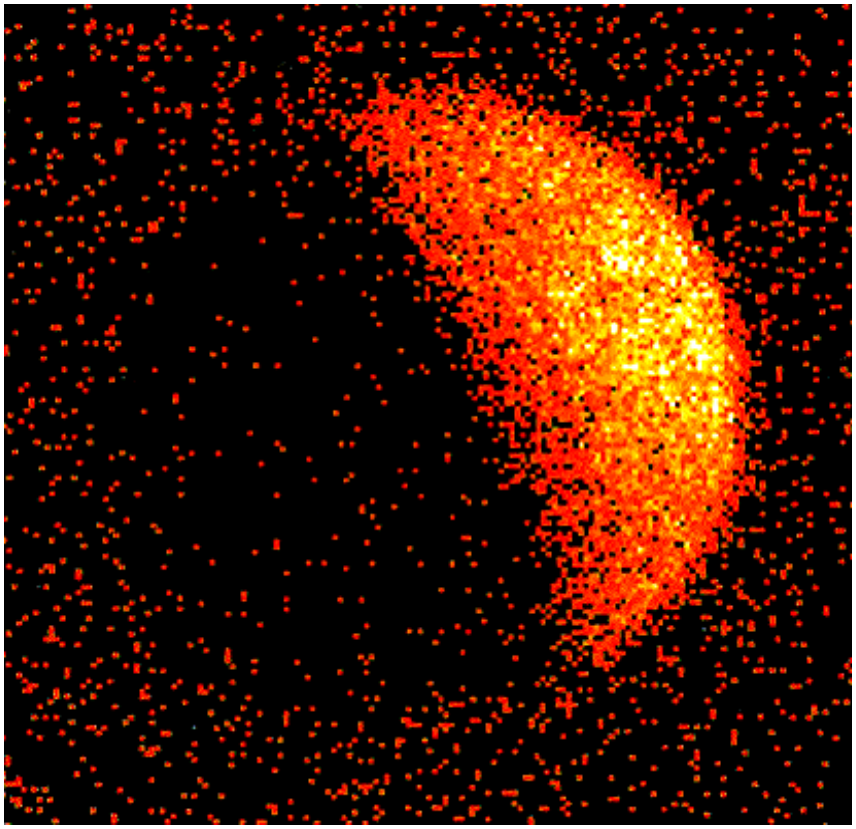

Figure 1: X-ray image of the moon with the *ROSAT* PSPC. Each individual point represents a measured X-ray photon. The crescent of the moon shows the reflected X-rays from the Sun. The dark side of the moon casts a clear shadow on the cosmic X-ray background radiation (MPE Garching).

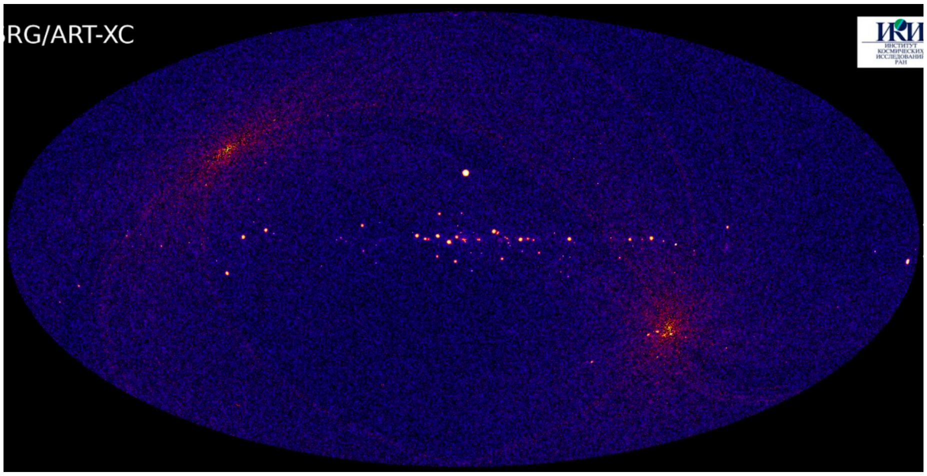

Figure 2) with the image of the Milky Way in visible light (Figure 1) the regions of the galactic plane bright in visible light appear darker in X-rays, because the diffuse emission in the background is absorbed. The areas above the Galactic plane, which are dark in visible light, appear in bright, colored X-ray light. These are the explosion clouds of dead stars that cover the entire sky like a hot fog. The extragalactic background radiation discovered by Riccardo Giacconi and his colleagues is visible only at higher energies. The Lockman Hole is located at the top left in the reddish area of the sky.

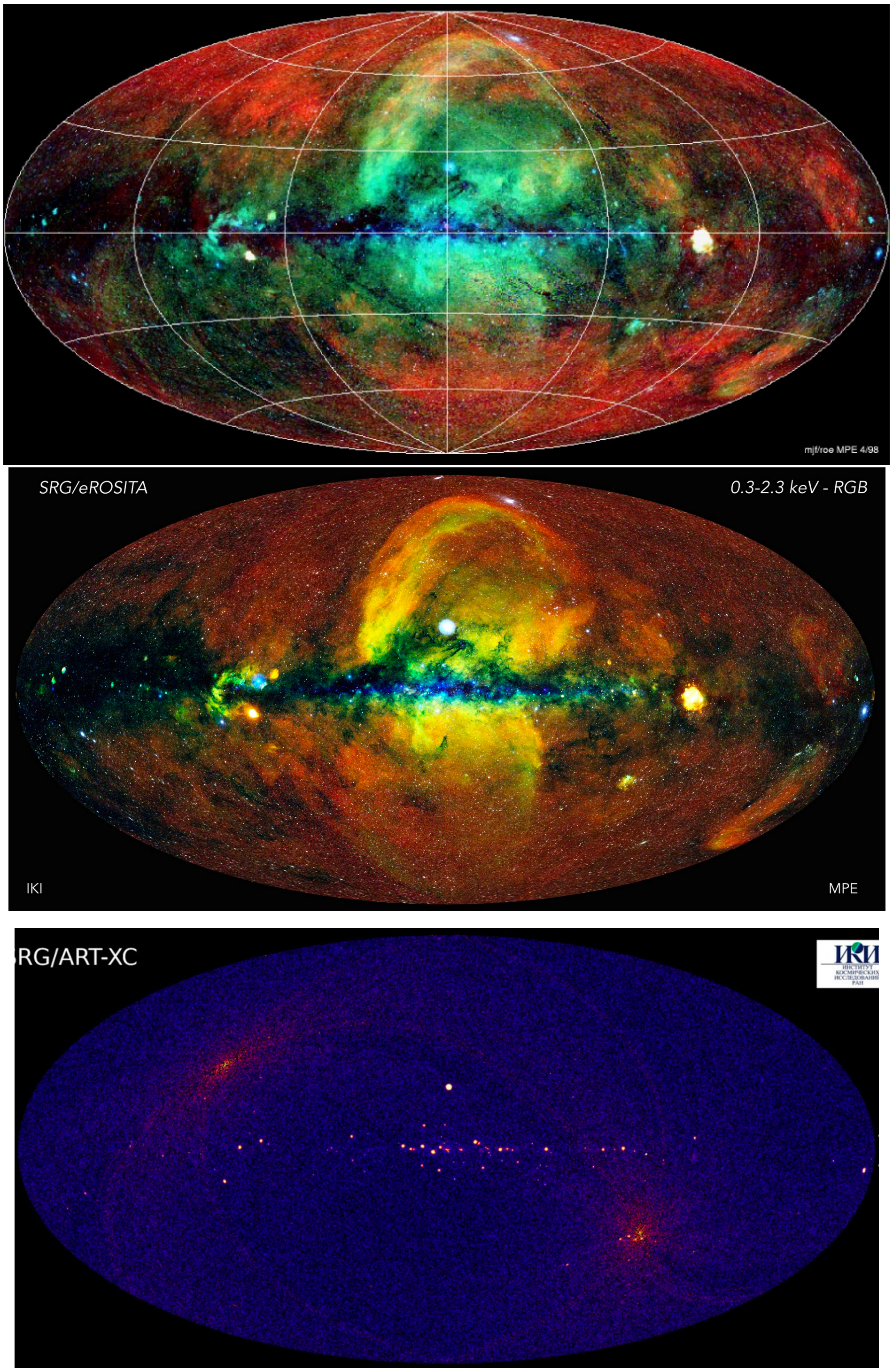

Figure 2: Top: ROSAT Panorama of the entire sky in X-rays as of 1992. The X-ray radiation is color-coded, soft radiation with temperatures of about 1 million degrees is red, correspondingly harder radiation with temperatures in the range from 3 to 10 million degrees is displayed in green or blue. In the middle of the figure is the Galactic Center. Middle: The same Map observed from the first eROSITA All Sky Survey eRASS:1 in the 0.1-10 keV band (MPE Garching). Bottom: the same map observed with the Mikhail Pavlinsky ART-XC telescope in the 5-15 keV band.

The detailed *ROSAT* deep surveys in the Lockman Hole began in spring 1991 with an exposure over about two days with the PSPC. A year later, a second equally long PSPC exposure followed. In addition to the two imaging proportional counters built by MPE, which were able to measure X-ray colors, the satellite also carried a High-Resolution Imager (HRI) X-ray camera, developed for NASA by Steve Murray at the Smithonian Astrophysical Observatory, which became the workhorse for the satellite after the proportional counter gas had run out. With this camera, we succeeded for the first time to win a 'Megasecond' exposure, i.e. one million seconds for observations in the Lockman Hole. All in all ROSAT has observed this field for about 1.4 million second (see Figure 48). Considering the fact that the satellite could effectively use only about half of the total time because of the occultations by the Earth, this corresponds to nearly an entire month of observation time. This is quite comparable with the most sensitive observations in other wavelength ranges, such as the famous '*Hubble Ultra Deep Field*' (see **Error! Reference source not found.**) and has set standards for future deep X-ray observations with *XMM-Newton* and *Chandra*. First with *ROSAT* and later with *Chandra* and *XMM-Newton* Giacconi's original dream has thus come true: the resolution of the X-ray background into discrete objects.[9] Practically, with these deep surveys in X-ray light we have made something similar to Galileo Galilei, who pointed his telescope on the Milky Way in 1609 and found that it consists of millions of individual stars. The diffuse X-ray glow in the sky could be resolved with the deepest X-ray observations into hundreds of millions of individual points of light across the whole sky.

Thereafter, the most tedious work was to obtain optical follow-up and spectroscopic identification as well as classification of the newly discovered X-ray sources. Taking spectra of hundreds of weak sources on large optical telescopes was a real Sisyphean task. With the help of these spectra X-ray sources have been identified and classified in order to be able to determine their redshift and thus correspondingly their age or their distance. The objects discovered in the deep surveys represented the faintest X-ray sources that anyone had seen before, and are typically very weak also in the visible light. To take optical spectra of those, we needed access to the largest telescopes in the world. Maarten Schmidt introduced me to the world of optical observations at large telescopes. Together with Don Schneider and Jim Gunn, he had developed the '*4-shooter*', a special spectrographic camera for the 5-meter telescope on Mount Palomar and I was invited to the first observing run with this instrument at that giant eye. Maarten, Don and Jim, three pioneers in the search for ever more distant quasars, are the main characters in Richard Preston's interesting biographical

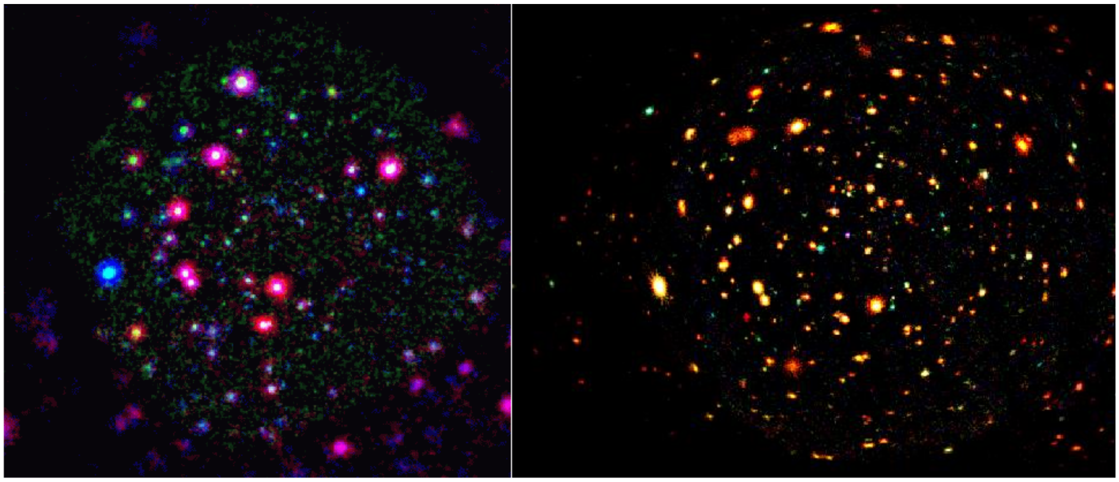

Figure 3: Deep X-ray survey in the *Lockman Hole*. The field is about as large in the sky as the full Moon. Left: the longest (1.4 Msec) and and most sensitive observation with the ROSAT satellite in false color. The data recorded with the 'color-sensitive' PSPC are red (very 'soft' X-rays, 0.1-0.5 keV), and blue ('soft' X-rays, 0.5-2 keV), with the data from the high-resolution HRI camera shown in green. Right: the X-ray color image of the same sky region recorded with XMM-Newton using an exposure time of about 1 Msec. The colors correspond to the energy ranges: red: 'soft' X-rays (0.5-2 keV), green: medium X-rays (2-4.5 keV) and blue: 'hard' X-rays (4.5-10 keV). (MPE Garching).

novel "*The First Light: In Search of the Infinity*",[10] which portrays the lives of the astronomers on 'the mountain' in great detail.

On my first day at Mount Palomar Maarten showed me the venerable 5-meter telescope. With a specially designed elevator we went up to the prime focus cabin, located more than 20 feet above the main mirror. In earlier times, astronomers had to squeeze into this tiny cabin for their observations, often throughout the whole night. Maarten is probably the astronomer who has been in this cage for the longest period of time. Then we climbed through the scaffolding of the dome interior out through a small hatch onto roof of this gigantic cathedral, on which otherwise only the technicians are allowed to stay for clearing snow. This was an absolutely spectacular introduction into optical astronomy!

After the first 10-meter Keck telescope had started its operations, Maarten and I travelled to Hawaii for several consecutive years in the spring to carry out observations in the Lockman Hole. Usually the astronomers are envied, because they can carry out their work in such a beautiful environment. However, the trip to the top of the Maunakea volcano at 4300 meter altitude on the Big Island of Hawaii is very long and arduous, in particular when you come from the other side of the Earth. You need multiple stops with layovers at airports, and have to sleep an additional night at the Hale Pohaku lodge halfway up the mountain in order to acclimatize. Unlike the tourists in shorts and slippers, usually crammed into the plane, the astronomers are heavily loaded with work material and with winter gear in the face of extreme cold on the mountain. Working at night at 4300 meters height is also no picnic. Every movement is difficult and because of the lack of oxygen can lead quickly to a stabbing headache. Your brain and eyesight are also not working at full speed. Maarten had therefore forbidden to carry out complicated calculations, or to make important short-term decisions in this environment. Every iota of the observing plan had to be prepared at lower levels. Nevertheless, the observing nights at the Keck telescope on the summit of Maunkea (and later on the Very Large Telescope of ESO on the summit of Cerro Paranal in Chile) were my fondest professional memories. This was, when I started to fall in love with Hawaii.

Later, the Keck Observatory more and more moved to remote observing, where the astronomers work at the headquarter building Waimea at the base of Maunakea and are connected to the night–astronomer and the technicians on the summit by a microwave radio and video link. But Maarten struggled for quite some time against this – in his opinion degenerate – way of doing astronomy. He wanted to hear and smell the telescope, periodically check the sky with his own eyes, and especially personally communicate with the night–astronomer, who operates the telescope. In fact, in Waimea it is rather common to have thick clouds and rain, while the most wonderful weather prevails at the summit. It is a strange feeling to travel half around the world, and then stay a few kilometers apart from your target of desire to carry out observations under a blanket of clouds. But in the meantime practically all observers and even most of the night assistants observe remotely, and many do not even travel anymore to Hawaii.

Back to science: After many years of optical observations, we had obtained a complete picture of the population of the sources of the X-ray background. We were able to show that most of the newly discovered X-ray sources were distant active galaxies, in the centers of which Black Holes were just well fed and therefore growing. The X-ray background radiation therefore stems from the feeding and growth phase of the entire massive Black Hole population in the Universe. All supermassive Black Holes we observe today in the centers of nearby galaxies must have grown in earlier cosmic times and have imprinted the light emitted during their accretion processes on the X-ray background. By measuring their redshift, we can place the sources into the context of their cosmic history. It turns out that the Black Holes with the highest luminosity, the so-called ‘quasars’, originated in a kind of ‘feeding frenzy’ a few billion years after the Big Bang, while the less luminous specimen came much later. This behavior is somewhat paradoxical, as in a hierarchically growing Universe one would expect that small structures are formed first, while larger ones grow later. Only in recent years we could understand this ‘downsizing’ effect, which has to do with the fact that in the early Universe galaxies are colliding with each other much more frequently than nowadays. As we will see in the next section, this process can feed Black Holes very efficiently, while later in the Universe the Black Holes are starving over long periods of time.

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[1] http, //nobelprize.org/nobel_prizes/physics/laureates/2002/giacconi-autobio.html

[2] Giacconi, R., Clark, G.W., Rossi, B.B., 1960; A brief review of Experimental and Theoretical Progress in X-ray Astronomy, Technical Note of American Science and Engineering, ASE-TN-49, Jan. 15 (1960).

[3] Riccardo Giacconi, Herbert Gursky, Frank R. Paolini, Bruno B. Rossi ; Evidence for X-Rays From Sources Outside the Solar System, Physical Review Letters 9, 439 (1962)

[4] Trümper, J., Pietsch, W., Reppin, C., Voges, W., Staubert, R., Kendziorra, E.,; Evidence for strong cyclotron line emission in the hard X-ray spectrum of Hercules X-1: ApJ 219, L105 (1978)

[5] Werner Heisenberg; Schritte über Grenzen. Gesammelte Reden und Aufsätze, R. Piper München (1971)

[6] Hoimar v. Ditfurth; Im Anfang war der Wasserstoff, Hoffmann & Campe, Hamburg (1972)

[7] Kippenhahn, Rudolf; (ibid.)

[8] Schmitt, J. H. M. M., Snowden, S. L., Aschenbach, B., Hasinger, G., Pfeffermann, E., Predehl, P., Trümper, J. : A soft X-ray image of the moon, Nature 349, 583

[9] Some publications about the resolution of the X-ray background into discrete sources with *ROSAT*, *XMM-Newton* and *Chandra*: Hasinger G., Burg R., Giacconi R., Hartner G., Schmidt M., Trümper J. & Zamorani G.: A deep X-ray survey in the Lockman Hole and the soft X-ray log N – log S, Astronomy & Astrophysics 275, 1 (1993); Hasinger G., Burg R., Giacconi R., Schmidt M., Trümper J., Zamorani G.: The *ROSAT* Deep Survey I. X-ray sources in the Lockman Field, Astronomy & Astrophysics 329, 482 (1998); Hasinger, G., Altieri, B., Arnaud, M., Barcons, X., Bergeron, J., et al. : *XMM-Newton* observation of the Lockman Hole. I. The X-ray data, Astronomy & Astrophysics 365, L45 (2001); Giacconi, R., Rosati, P., Tozzi, P., Nonino M., Hasinger, G., et al. : First Results from the X-ray and Optical Survey of the Chandra Deep Field South, Astrophysical Journal 551, 624 (2001); Brandt, W. N., Hornschemeier, A. E., Alexander, D. M., Garmire, G. P., Schneider, D. P., et al.: The Chandra Deep Survey of the Hubble Deep Field North Area. IV. An Ultradeep Image of the HDF-N, Astronomical Journal 122, 1 (2001)

[10] Richard Preston (ibid.)