Riccardo Giacconi

1931–2018

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
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NATIONAL ACADEMY OF SCIENCES

RICCARDO GIACCONI

October 6, 1931–December 9, 2018

Elected to the NAS, 1971

Photography by ESO

By Harvey Tananbaum, Ethan J. Schreier, and Wallace Tucker

Riccardo Giacconi, the "Father of X-ray Astronomy," Nobel laureate, and one of the most influential figures in astrophysics over the past 60 years, died on December 9, 2018, at the age of 87. With a career spanning the electromagnetic spectrum, Riccardo opened up new windows for observing the universe and revolutionized "big astronomy." Many in the astronomy community continue to base their research on data from observatories he conceived, built, and/or directed. Riccardo was well-versed in the classics and often spoke of being driven, like Odysseus, to pursue virtue and knowledge. We three were privileged to accompany him in one way or another on his epic journey as friends and colleagues beginning in the late 1960s when, still in our twenties, we came together at American Science and Engineering (AS&E) in Cambridge, Massachusetts.

Riccardo's outstanding scientific capabilities were well-matched by his extraordinary leadership and management skills. He had a deep belief in a scientific approach to problem solving and to establishing systematic processes. He insisted that instruments and observatories be built to answer driving scientific questions. Another key to his success was the legendary dedication and drive of the research teams he assembled, which could be traced directly to Riccardo's deep commitment to establishing an environment of intellectual honesty and trust.

The discovery in 1962 by Riccardo and colleagues at American Science and Engineering (AS&E) in Cambridge, Massachusetts, of both a pervasive X-ray background radiation and Scorpius X-1, the first extra-solar X-ray source, marked the birth of X-ray astronomy. Giacconi's group then developed and operated the first X-ray satellite, Uhuru, which was launched in 1970 and led to the discovery of black holes. In 1973, Giacconi's group moved to the Harvard-Smithsonian Center for Astrophysics (CfA), also in Cambridge, where they developed the Einstein X-ray Observatory, the first imaging X-ray telescope for extra-solar astronomy. Launched in 1978, Einstein demonstrated beyond doubt the importance of X-ray imaging and led to the discovery that essentially all types of astronomical objects and systems emit X-rays.

One byproduct of this mission was the development of procedures and techniques to plan, schedule, and archive the Einstein observations, thus making the observatory accessible to the entire astronomical community. This model of open access, new for space missions at the time, has now been adopted by all NASA observatories and indeed by most major observatories worldwide. In 1976, together with Harvey Tananbaum, Giacconi proposed Einstein's successor, NASA's Chandra X-ray Observatory, which was launched in 1999. Chandra, having exceeded 20 years of operation, remains without peer for its ability to produce sub-arcsecond X-ray images and has established itself as one of the most productive observatories in any wavelength range.

Giacconi moved from the CfA to the newly created Space Telescope Science Institute (STScI) in Baltimore, Maryland, in 1981 as its first permanent director. In that capacity, he carried over and expanded many of the procedures developed for the Einstein Observatory and played a critical leadership role in the development of corrective optics for the flawed mirror of the Hubble Space Telescope. In 1993, Giacconi moved to Garching, Germany, where he served as director general of the European Southern Observatory (ESO) for nearly seven years. At that time, ESO's Very Large Telescope was under construction, and he instituted management techniques that were important for its successful development and operation. In 1999, he returned to the United States to become president of Associated Universities, Incorporated (AUI), where he instituted many of the same operational principles for radio telescopes managed by the National Radio Astronomy Observatory (NRAO) and oversaw the North American role in the planning and international agreements for the Atacama Large Millimeter/submillimeter Array (ALMA).

Early Years

Born in Genoa, Italy, on 6 October 1931, Riccardo was the only child of Elsa (Canni) and Antonio Giacconi. Elsa, a high school teacher of mathematics and physics, was the co-author of many textbooks on geometry that were widely adopted in Italy. Antonio was a shopkeeper, accountant, trade-union leader, and outspoken anti-fascist. In 1937, Antonio and Elsa separated. Because of the breakup of the family and the chaos caused by World War II, Riccardo was shunted from one place to another. Reflecting on the impact of the war on his childhood, Riccardo said that whereas he did not think that the war was a profoundly traumatic experience for him, he did know that "the war made me grow up faster than might have happened otherwise."[1] After the war, he attended high school in Milan and went on to study physics at the University of Milan. It was in Milan during his high school days that Riccardo met Mirella Manaira. After reconnecting several years later, they would marry in 1956, and she would be "a source of strength and a valued confidant" for the rest of his life.[2]

Riccardo received his doctorate in 1954 from the University of Milan, working in high-energy physics. At that time, the only practical way to study high-energy nuclear reactions was through the detection and analysis of the interaction of high-energy cosmic rays, primarily protons, with atomic nuclei in the atmosphere. For his thesis research, he spent about two years at the Testa Grigio Observatory (elevation 3500 meters) in the Italian Alps. Although he learned much about the conception, design and building of detectors, Riccardo was frustrated by the lack of "action:" he spent about two years with his cosmic ray detector in an alpine Quonset hut and obtained eighty high-energy cosmic-ray detection events.

Upon graduation, Riccardo was offered a position as lecturer in the Physics Department at the University of Milan. About this time, he began doing research with Giuseppe Occhialini, a noted cosmic ray physicist, who gave Riccardo the responsibility for the design and construction of bigger and better cosmic ray detectors. Describing Occhialini as "by far the most important influence on my university life," Riccardo "learned from him more by osmosis than through any formal training, in informal and frequent discussions as we traveled to meetings or to visit other laboratories."[3] It was Occhialini who advised Riccardo to "go west, young man" and work with the cosmic ray physicist Robert Thompson at Indiana University.

Soon thereafter, Riccardo applied for and received a Fulbright fellowship at Indiana University and later Princeton University. At Princeton, he met and worked with Herbert Gursky on cosmic ray experiments. According to Riccardo, "We built equipment, worked like fiends, analyzed data, and declared failure."[4] When his Fulbright fellowship expired, he accepted a position at AS&E, a high-tech company formed in Cambridge, Massachusetts, in 1958 by Martin Annis, and he moved to the Boston area with Mirella and his two daughters, Guia and Anna, in September 1959.

X-ray Astronomy at AS&E and CfA

Shortly thereafter, AS&E board chair and Massachusetts Institute of Technology (MIT) professor Bruno Rossi suggested at a party that Riccardo look into the possibility of developing a program to search for sources of cosmic X-rays. A group led by Herbert Friedman of the Naval Research Laboratory had previously observed X-rays from the Sun but had failed to detect them from sources beyond the solar system. Based on the strength of the solar X-rays, this was not surprising, and it seemed unlikely to many astronomers that X-ray astronomy would be a productive undertaking.

Riccardo was unconvinced. He suspected that the problem lay not in the stars, but in the efficiency of the X-ray detectors and an underestimation as to what the universe could provide. Determined not to be thwarted by the dearth of data as he had been in his cosmic ray research, he undertook an investigation of ways to concentrate weak X-ray signals, i.e., how to build an X-ray telescope. Drawing from previous considerations of potential X-ray microscopes, he quickly concluded that a parabolic mirror could focus X-rays impinging at near-grazing incidence angles, while Rossi added the notion of nesting surfaces to increase the collecting area.[5] Riccardo undertook a research program to design and build a fully imaging X-ray telescope using two reflecting surfaces (as conceived by Hans Wolter for X-ray microscopes).[6]

Realizing that the development of an X-ray telescope would take a decade or more, Riccardo began work on a program using conventional, rocket-borne Geiger counters. After NASA rejected his proposal, he was able to secure funding for this program from the Air Force Cambridge Research Laboratory. Although the ostensible goal was to detect fluorescent X-rays from of the Moon, Riccardo was on the hunt for bigger game. Working with Frank Paolini and Herbert Gursky, he developed detectors with a much wider field of view and about fifty times more sensitivity than ones flown previously.

On June 18, 1962, after two previous launches had ended in failure, Riccardo and his group achieved success. In the five minutes that the rocket was above the atmosphere, they detected a strong source in the direction of the constellation Scorpius, which they named Scorpius X-1, as well as an all-pervasive X-ray background radiation (see Figure 1). Commemorating these momentous discoveries fifty years later, along with all that had followed, Riccardo wrote:

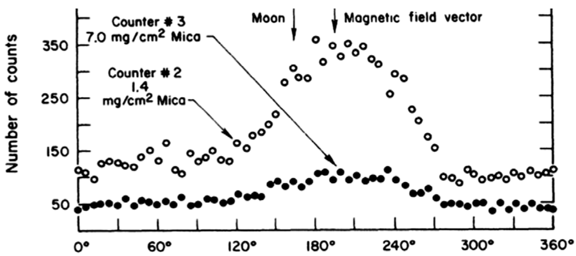

Figure 1: Data from 1962 rocket flight showing discovery of Scorpius X-1 as large bump in Counter #2 data and All-Sky X-ray Background as residual excess to either side. (Photo provided by *Physical Review Letters*.)

“Successes of X-ray astronomy were not a fluke. [They] resulted from bounty of Nature, aspirations of many people, rigorous and methodical research effort, and development of new technology and new operational approaches.”[7]

Riccardo moved quickly to exploit this new window for exploring the universe, proposing with Gursky a bold five-year X-ray astronomy program that included more rocket flights, an X-ray satellite to survey the entire sky, and eventually an X-ray telescope. Applying his strong conviction and remarkable persistence, Riccardo persuaded NASA to support the initial phases of the program. At the time, he did not imagine that it would take nearly forty years to fully realize his vision.

With funding from NASA, Riccardo’s group initiated the design and development of the first satellite dedicated to X-ray astronomy. Although Riccardo originally planned on developing the entire satellite at AS&E, NASA was unwilling to delegate full responsibility for the mission to a small, private company. Eventually, NASA decided to establish a series of Small Astronomy Satellites (SAS) managed by Goddard Space Flight Center. The Applied Physics Laboratory at Johns Hopkins University was responsible for the spacecraft, including the power, communications, and pointing control systems. Riccardo, as Principal Investigator (PI) for this first SAS mission, was responsible for the science payload. The interfaces between the payload and the spacecraft were very simple—four bolts for mechanical attachment and a single multi-feed electrical connector.

Riccardo continued to refine what we all later came to refer to as his science systems engineering approach. Engineers and scientists worked side by side to establish requirements, develop a design, construct and test the hardware, and plan the operations for the satellite. His philosophy for the science payload emphasized “soft failures” with redundancies and fallback options so that single failures had a low likelihood of causing loss of mission. For example, there were two banks of proportional counters facing in opposite directions, multiple techniques for reducing background, two sets of electronics that could be connected to either bank of detectors, and multiple attitude sensors for stars brighter than fourth magnitude, the Sun, and the Earth’s magnetic field.

This first Small Astronomy Satellite mission (SAS-A) was launched into an equatorial orbit on December 12, 1970, from an Italian-operated platform off the coast of Kenya (see Figure 2), with a science payload team at launch comprised of Riccardo as PI, Harvey Tananbaum as project scientist, Richard Goddard as mechanical engineer, and Stan Mickiewicz as electrical engineer. In recognition of the launch occurring on the

Figure 2: Riccardo, with his then ubiquitous pipe, riding on powered raft to Uhuru launch platform off coast of Kenya.
(Photo provided by Harvey Tananbaum.)

anniversary of Kenyan Independence Day, Riccardo took the lead in renaming the satellite Uhuru ("freedom" in Swahili). NASA was initially unhappy with that step, but Riccardo's insistence on using Uhuru in scientific papers and media discussions soon convinced the agency to accept the new name.

In a departure from the traditional approach of mailing data tapes from NASA to science teams four to six weeks after the observations were taken, Riccardo negotiated transmission of 20 percent of the raw data from the ground station at Quito to Goddard and then on to AS&E within twenty-four hours of the observations. Even before launch, the team developed software to analyze the data, enabling us to rapidly rearrange the observing schedule and satellite configuration to follow up and exploit discoveries.

On a personal level, although junior scientists, we three and several other colleagues received assignments that challenged us to our limits while providing opportunities to develop technical, management, scientific, and communications skills. Riccardo met weekly with the Uhuru science group. In these often-stormy sessions, there was wide-open give and take. Ideas were floated with abandon and shot down remorselessly. There was respect for one and all, but no one was sacrosanct and everyone, including Riccardo, had to defend their ideas based on logic and scientific merit. After the launch, Riccardo blocked off part of each working day to meet with the science team to review the latest data, to further examine data of particular interest to him, and to develop strategies for upcoming observations. The underlying philosophy was to do the most promising scientific observations immediately, given the possibility that the mission could fail at any time.

A primary goal for Uhuru was to survey the entire sky to detect, locate, and identify new X-ray sources. The Fourth Uhuru Catalog listed more than three hundred newly discovered X-ray sources, increasing the known number by more than tenfold. One of the major discoveries was the detection of extended emissions associated with several clusters of galaxies, with the X-rays most likely produced via thermal bremsstrahlung from gas with temperatures of fifty to one hundred million degrees filling the space between the many galaxies comprising a cluster.

Unquestionably, the most significant result from Uhuru was the revelation that the luminous X-ray sources in our Milky Way galaxy are powered by accretion onto compact stars in binary systems. The path to this understanding took a number of twists and turns during the first year and a half of the mission (see the Nobel Prize website biography on Riccardo and its references for additional details).[4] Early on, a number of scans were oriented so as to traverse Cygnus X-1, discovered several years earlier and reported to vary in intensity on timescales of months. Only nine days after launch, Riccardo's colleague and close friend Minoru Oda, who was visiting from Japan, spotted a 25-percent change in intensity of Cygnus X-1 on a timescale of one second. Despite many attempts to search for a periodicity with further Uhuru observations and rocket and balloon flights by various other X-ray groups, none was found. A 1974 rocket flight by the Goddard team detected large intensity changes on a millisecond timescale, suggesting a source size as small as 300 kilometers.

While Cygnus X-1 remained a mystery, Riccardo and a few others, including Ethan Schreier, turned their attention to Centaurus X-3 (Cen X-3). Observations taken around one month after launch displayed large amplitude, apparently periodic signals with pulses spaced by approximately 5 seconds during a 20-second pass across the source. Over a day or two, the source intensity also varied between high states and low states that differed by a factor of ten. A few months later, individual transits of Cen X-3 were extended to durations as long as 150 seconds (see Figure 3) by adjusting the spacecraft rotor speed to slow down the satellite spin rate by a factor of seven, utilizing this capability in a manner not foreseen before launch. Analysis of these longer exposures focused on the pulsation period and its observed changes over time. The initial publication reported periodic

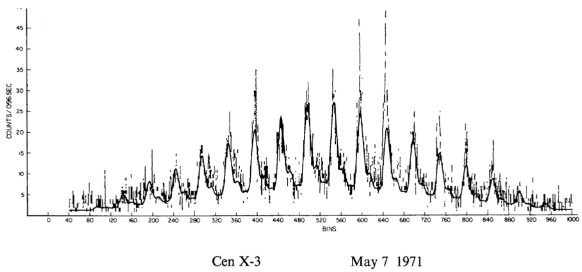

Figure 3: Uhuru detection of 4.8 second pulsations from Centaurus X-3. Counts per 0.096 second bin plotted vs bin number with fit shown by darker curve. Triangular envelope is imposed by response of mechanical collimator as satellite scans across source. (Photo provided by D. Reidel Publishing Co.)

pulsations with a period of approximately 4.8 seconds and possible abrupt changes, along with unexplained intensity variations. In retrospect, more experienced astronomers might have quickly concluded that the period and intensity changes were tied to Cen X-3's being a member of a binary star system. But it waited for a later paper for us to assert the binary interpretation. A possible explanation for this state of affairs is that Riccardo and essentially the entire team had been trained as physicists and were, in some ways, novices at astronomy. For example, no one was familiar with the binary mass function, and the team ended up rederiving it.

The binary revelation came several months later when Rich Levinson and Ethan Schreier connected additional Uhuru observations to detect a clear pattern of regular intensity changes with repetition on a 2.087-day timescale. Analysis of the pulsations using that rubric quickly revealed a sinusoidal timing pattern, with the pulses appearing closer together as the X-ray source approached the observers and spaced further apart as the X-ray emitting component moved away on an orbit around its binary companion. The timing analysis provided precise measures for many of the orbital parameters and a period precision of one microsecond. Subsequent observation of Cen X-3 showed the period decreasing by 3 milliseconds over eighteen months. With the spin rate increasing, conversion of rotational energy by analogy to radio pulsars could not be invoked to explain the X-ray emission. Accretion of matter from the companion star onto the compact star (eventually shown to be a neutron star for Cen X-3) became the widely accepted mechanism to explain all of the Cen X-3 observations, as well as the power source for many of the previously mysterious galactic X-ray sources.

In the meantime, an improved X-ray position from an MIT rocket flight along with ground-based optical observations provided a candidate identification for Cygnus X-1 with a high-mass star. Monitoring of the X-ray light curve with regular Uhuru scans over nearly two years revealed intensity and spectral shifts—now called a state change—correlated in time with the appearance of a radio source coinciding positionally with the proposed optical counterpart. Optical data obtained by Webster and Murdin and independently by Bolton showed that this star was in a binary system with a 5.6-day period and an unseen secondary with a likely mass of around six times that of our Sun—of order twice the theoretical limit for a neutron star. Summarizing this trail, Cygnus X-1 is compact based on its rapid time variability, is identified with the binary star system via the correlated X-ray/radio changes and the positional coincidence of the radio and optical system, and has an estimated mass of order six times the Sun based on the optical period and mass function. These parameters conclusively demonstrate that Cygnus X-1 is a black hole, proving the existence of an object that had been conjectured but had previously eluded detection.

While working on SAS-A/Uhuru through the late 1960s, Riccardo had continued to advocate for X-ray telescopes to enable detailed observations of X-ray sources in the Milky Way galaxy and beyond. A few months before the December 1970 Uhuru launch, he led a team of scientists from AS&E, MIT, Columbia University, and Goddard Space Flight Center, proposing as a consortium to be responsible for two telescopes and the science instruments on a mission they called the Large Orbiting X-ray Telescope (LOXT). Their proposal was accepted for study as one of four missions comprising NASA's High Energy Astronomy Observatories (HEAO) program. Early on, Riccardo envisioned LOXT as a facility that would be a national observatory open to all astronomers.

In 1973, substantial cost growth on NASA's Viking program to Mars along with interest in beginning what eventually became the Hubble Space Telescope led NASA to cancel the HEAO program. Working behind the scenes, Riccardo and a few leaders for other HEAO instruments convinced NASA to convert the cancellation to a suspension. For the next several months, Richard Halpern, the NASA headquarters manager for HEAO, and the engineers at Marshall Space Flight Center (MSFC) worked with the HEAO science teams to construct a down-sized program with three somewhat reduced missions. LOXT was advanced from its original third slot to become the second HEAO mission, but with a single, substantially smaller telescope and a much-reduced instrument suite. As development of the HEAOs proceeded, NASA opted for a low-earth orbit with gas jets rather than magnetic torquers for unloading momentum from the reaction wheels. These decisions may have been in response to pressure from the Office of Management and Budget to cap science mission costs by limiting their operating life. NASA further explained that the gas-jet systems were more reliable and lower cost, but these decisions assured that the HEAO missions would have a modest lifetime, initially established at one year. Eventually, the HEAO-2 telescope mission (renamed Einstein Observatory after launch) operated for nearly two and a half years, aided by judicious management of momentum build-up by pairing of appropriate targets and thereby slowing the depletion of the control-jet gas.

An innovative approach utilized for Einstein and subsequent X-ray observatories, including Chandra and the proposed Lynx observatory, involved a fiducial light system to significantly relax pointing requirements. Riccardo and the LOXT team realized that the relatively low counting rates enabled time-tagging for individual X-ray events. In turn, absolute pointing only needed to keep the target near the "sweet spot" in the center of the field of view while the fiducial system enabled high precision tracking of where the instrument and telescope were looking on the sky. A few light-emitting diodes rigidly mounted to each detector provided signals that were relayed back through the X-ray telescope and reflected from a corner cube mounted to the telescope to direct the light into the aspect camera. Data taken at one-second intervals showed the location of the diode images (and thereby the telescope and detector orientation) relative to the star images captured by the aspect camera. With gyroscopes recording the small motions of the observatory on timescales shorter than a second, the system provided a precise location in the sky for every photon imaged by the telescope without the need to keep the telescope precisely pointed. In addition, this approach eliminated the need for on-board processing and allowed the images to be reconstructed after the fact on the ground.

In 1973, Riccardo moved with a core group to the newly organized Harvard–Smithsonian Center for Astrophysics (CfA), where he led the High Energy Astrophysics Division (HEA) and also became a professor at Harvard University. The decision to move was motivated in large part by Riccardo's sense that a national facility of the sort he had envisioned for LOXT would fare better if it were sited in a research/academic environment rather than at a private company. The transition to the CfA occurred just as the reconstituted and reduced HEAO program was being approved. Riccardo retained his overall scientific leadership as the PI for what became the Einstein Observatory.

The merging of X-ray astronomy into the mainstream of astronomy accelerated with the 1978 launch of Einstein. Its imaging capabilities revealed that essentially all types of astronomical objects, from nearby stars to distant quasars, radiate X-rays. For Riccardo, his dreams of imaging portions of the celestial sky with an X-ray telescope were realized nearly twenty years after he first considered such an instrument. In looking back on this time, he wrote of realizing that "we of the consortium had made an advance in observational astronomy such as had rarely occurred in its history….I had no doubt that X-ray astronomy would make unique contributions to the study of the universe."[8]

Riccardo's personal research with Einstein focused on deep exposures reaching approximately a factor of one thousand fainter than Uhuru, with many of the observed sources being associated with quasars and some lower luminosity supermassive black holes, all powered through release of gravitational potential energy from infalling gas in the central regions of their host galaxy. The sources detected in these exposures on previously "blank fields" with no known bright X-ray sources accounted for 25-35 percent of the few keV all-sky background (XRB) first detected in the 1962 discovery flight. With Einstein, Riccardo was moving along the path towards resolving that background and determining its origin.

Through the 1970s, Riccardo was unable to achieve his vision of a national X-ray observatory for Einstein. Neither the Smithsonian Astrophysical Observatory nor Harvard (institutionally or staff-wise) were particularly supportive of hosting such a facility, and NASA had little interest in organizing such a scientific institution. Undeterred, Riccardo and his team took the steps to initiate a guest-observer program enabling all astronomers to use Einstein. The first actions occurred during the calibration of the telescope and science instruments at MSFC in 1976. Besides the tools to organize and track the large number of measurements, the team provided software and hardware to process and analyze the raw data and to archive the results. Moreover, the large amount of data illustrated the computing capability that would be needed to process flight data at real-time speed - handling at least one day of data per day.

With agreement from NASA, the consortium established a one-year proprietary limit for data acquired under their guaranteed observing time and also allocated a fraction of the observing time, averaging about 25 percent over the mission lifetime, to guest observers. Riccardo's group at CfA, under the leadership of Ethan Schreier, developed tools for simulating potential observations, for data processing and calibration, for efficient observation scheduling, and for data archiving and distribution. The team also provided direct support through assisting non-experts in accessing and analyzing their data and understanding the observatory's performance.

This Einstein experience provided a superb training ground for Riccardo, for the CfA X-ray group, and for the larger astronomical community on how to establish and operate national facilities that enabled astronomers worldwide to propose their best ideas for using the world's best space- and ground-based facilities. This approach extended the pioneering steps to competitively allocate the observing time taken at the National Radio Astronomy Observatory under the "open skies" leadership of David Heeschen in the 1960s. It has now been widely adopted. Riccardo personally took it to the Space Telescope Science Institute for Hubble, to the European Southern Observatory for the Very Large Telescope, and to Associated Universities, Inc. for the Atacama Large Millimeter/

Submillimeter Array. It has also been implemented at CfA for the Chandra X-ray Observatory and is in use for many other observatories and missions.

In 1976, cognizant of the limited lifetime projected for Einstein, Riccardo and Harvey Tananbaum proposed its successor, the Chandra X-ray Observatory. Launched in 1999 and now beyond twenty-one years of operation, Chandra remains without peer in the X-ray band for its sub-arcsecond angular resolution and its sensitivity for studying objects as diverse as exoplanets, neutron stars, black holes, clusters of galaxies, dark matter, and dark energy. Although Riccardo would move on to new challenges, he remained involved with Chandra, pursuing an understanding of the soft X-ray background radiation discovered in 1962. His research, along with that of others, reached an ultimate exposure time of seven million seconds for the Chandra Deep Field South, resolving over 90 percent of the few keV X-ray background. Together with data from the most powerful optical, infrared, and radio telescopes on the ground and in space, these observations confirm that the background is primarily produced by accreting supermassive black holes in galaxies distributed near and far, with significant numbers of normal and star-forming galaxies beginning to appear (but only contributing a modest amount to the X-ray background) at the lowest fluxes reached by Chandra.

Hubble and the Space Telescope Science Institute

In 1981, Riccardo moved on to the next major challenge of his career, revolutionizing optical astronomy. The astronomy community had long wanted to have a large optical telescope in space—an effort that had begun in the late 1940s, led in large part by Lyman Spitzer and later joined by John Bahcall. By the late 1970s, the program was underway. The scientific community insisted that the science operations of such a large, unique, and expensive new facility—the first major international optical observatory in space, later to be christened Hubble—be managed by the community itself.[9] This recommendation, based on a National Academy of Sciences study, was not universally accepted, especially within NASA, where it was customary for the centers to operate major facilities. Nonetheless, a competition took place for a community-based organization to conduct the science operations of the telescope. Note that some tension persisted for a number of years, even after what would become the Space Telescope Science Institute (STScI) proved its worth in the successful conduct of the Hubble mission, including its major role in rescuing Hubble when its optical flaw was discovered.

The Association of Universities for Research in Astronomy (AURA), which operated Kitt Peak National Observatory in Arizona and Cerro Tololo Inter-American Observatory in

Chile, won the contract to establish an institute to conduct the science operations for the new telescope. Considering the qualities that the director of such an institute would need—wide recognition by the science community, knowledge of both science and engineering, leadership and management ability, and an ability to strongly represent the needs of science in the NASA system—AURA conducted an international search, leading to the selection of Riccardo as the first director of the STScI. He was simultaneously appointed professor of astrophysics at the Johns Hopkins University.

Riccardo proceeded to build an entirely new institute from scratch, assembling a core staff with expertise in the operational, engineering, and scientific disciplines necessary to operate Hubble. Recognizing the need to transfer the scientific operations philosophy from his X-ray group to the optical community, Riccardo recruited Ethan Schreier to oversee the Hubble operations and data system. He also recognized the need to have a quality science staff, on a par with the best university departments, so he established a tenure process and insisted that time be reserved for the staff to carry out their own research.

Innovations introduced by Riccardo and his staff for Hubble included: a formal data archive with a funded data-analysis program, the distribution and archiving of calibrated data, an AI-based planning and scheduling system, reserved time for large and "key" programs, and freely distributed portable data analysis software. The goal was to make Hubble usable by the entire astronomy community, not just by experts in a given discipline or a given instrument. The system produced calibrated data, but users also had access to the calibration software, allowing them to redo the calibrations if necessary. The data analysis software system, including the calibration algorithms, was written to be portable, so that users could run it on their own computers. Other observatories adopted similar standards, facilitating joint analysis of observations taken at different wavelengths. The archive included both raw and calibrated data; and observations were open to all after a one-year proprietary period. Within only a few years after launch, more data was being distributed from the archive than was being added via new observations.

But the path to Hubble's success was not straightforward. NASA had chosen to outsource the operations software system, and without adequate science oversight the software could not meet the needs of the science community. STScI gradually took over responsibility for the system and did a major overhaul ranging from a guide star selection system, to an AI-based planning and scheduling system, a science-friendly commanding system, and an efficient capability to track moving objects. After a dramatic shuttle deployment

Figure 4: Riccardo Giacconi, Ethan Schreier, and Rodger Doxsey (left-to-right) at STScI during Hubble activation in spring 1990. Individual in foreground not identified. (Photo provided by Ethan Schreier.)

in 1990 and a careful activation period (see Figure 4), the infamous flaw in Hubble's optical system was discovered, with images not being as sharp as predicted. Owing to scheduling and cost considerations, NASA and the telescope subcontractors had not conducted any pre-launch end-to-end test for Hubble, resulting in the error going undetected on the ground. The Institute organized a number of cross-discipline working groups to address the problem. With NASA's support and under Riccardo's guidance, both near- and long-term solutions were developed, and by the mid-1990s, Hubble had become arguably the most productive telescope ever.

Riccardo also instituted the first community-operated grants program to support Hubble users and developed a "Hubble Fellows" program to support young astronomers. Both became models for other missions and disciplines. Riccardo recognized the importance of sharing Hubble's scientific discoveries and beautiful images with the public and instituted a vigorous public outreach program for Hubble.

VLT and the European Southern Observatory

In 1991, Riccardo and Mirella's son Marc died in an automobile accident. Although he continued working at STScI, the "continued and painful reminders of devastating grief" associated with Baltimore led Riccardo to accept a position as director general of the European Southern Observatory (ESO) in Garching, Germany. Riccardo held that position from January 1993 through July 1999, during which time his primary focus was the building of the Very Large Telescope (VLT).

Upon arriving at ESO, Riccardo realized that VLT required substantial technical breakthroughs while also presenting financial challenges, with projected design and construction costs around six times the annual ESO budget. Notwithstanding ESO's successes in developing the New Technology Telescope (NTT) in the 1980s and operating a number of telescopes at La Silla in Chile, Riccardo was concerned that ESO was not organized in a way needed to succeed on a project with the scope of VLT. He implemented organizational and administrative changes that established unambiguous statements of tasks and responsibilities, modernized the personnel processes, strengthened connections and communications between the operations team at La Silla and the ESO offices in Garching, and promoted the concept of a single observatory with shared goals for all. Riccardo placed priority on initiatives with potentially high scientific return, created an Office for Science within ESO, and established the concept of service to the astronomy community as the premier objective of the observatory.

Riccardo also recognized that changes would be needed at La Silla, which operated fifteen telescopes when he arrived. He appointed a special working group to review their activities, to solicit inputs from European astronomers, and to recommend priorities for La Silla in the coming VLT era. The ESO Council's decisions, based on those recommendations, allowed Riccardo to close obsolete telescopes and to focus resources to upgrade others, particularly the NTT for which such plans had already been initiated. The NTT command and control systems were completely updated, taking advantage of software under development for VLT. NTT upgrades also involved new calibration, operation, and maintenance procedures, installation of the new VLT systems for active telescope control, and installation of new optical and infrared detectors including early versions of instruments being developed for the VLT. In essence, the NTT became a testbed for software, hardware, and processes needed for the VLT.

Riccardo prioritized ESO development of state-of-the-art charge-coupled devices with high-speed, low-noise, multiport readouts; high quantum efficiency over a broad wavelength band; large format; and a small number of chip defects. In addition, in anticipation of the expected high rate of data flow from the VLT, he transformed data management at ESO by automating various steps, including handling proposals, program selection and scheduling, calibration and pipeline data processing, and archiving and data distribution.

Throughout his time as ESO director general, Riccardo applied his practiced science systems engineering approach to building the VLT. He reviewed all of the data on astronomical seeing collected at Cerro Paranal, Chile, from 1987 to 1992 and concluded that the VLT should be sited there. Along with other team members, he recognized that the 8-meter diameter, 17.5-cm thick primary mirror for each of the four VLT telescopes presented unique engineering challenges. Early on, he suggested that two parallel contracts be awarded to build prototypes of the support structure for the primary mirror to evaluate ease of access for maintenance on the active control actuators as well as convenience for cabling and operation. The secondary mirror brought its own challenges, with a design that accommodated three foci while demanding stiffness sufficient for relatively quick movement. Eventually, beryllium was selected over silicon carbide for the secondary. Recognizing the difficulty in achieving required telescope stability in the presence of thermal gradients and high winds, Riccardo organized a separate systems engineering group at ESO to focus on the telescope enclosure through modeling and systems analyses.

Prior to Riccardo's arrival in 1993, ESO was losing about nine months of schedule each year towards completion of the VLT; over the next five years only nine months in total was lost. The first VLT image was obtained in May 1998 with angular resolution of about 1/4 arcsecond. This remarkable turnaround stems in part from the structural changes Riccardo implemented for management and administration as well as his deployment of modern tools such as work breakdown structures (WBS), management information systems (MIS), and annual performance reviews to evaluate staff effectiveness. Success also stemmed from the motivation he provided to the staff, instilling a shared vision and commitment and pride in reaping the benefits of increased productivity and technical breakthroughs.

While all of this work was proceeding, Riccardo also had to deal with a changing political environment in Chile, leading him to question whether the VLT could be sited atop Cerro Paranal. Issues involved ownership of the land, applicability of Chilean labor laws versus policies in effect at ESO, and the initial unwillingness of ESO to provide guaranteed observing time to Chilean astronomers (in contrast to arrangements for U.S. telescopes in Chile). Following unsuccessful legal skirmishes and a few poorly handled press conferences, ESO and Riccardo realized that they needed to convince the top levels of the Chilean government to become involved. Ricardo met over a private lunch with the Chilean foreign minister José Insulza, followed by a small meeting at the home of Chilean president Eduardo Frei Ruiz-Tagle. Positive steps ensued, culminating with the ratification in late 1996 of a formal agreement approving the construction of VLT atop Paranal.

During this time, Riccardo took an interest in the 15-m diameter millimeter wave telescope at La Silla, which led him to assess future plans for radio telescopes, including the Large Southern Array under consideration in Europe and a possible U.S.-Netherlands collaboration on the Millimeter Array project. He concluded that it might be possible to compromise on differences in objectives and approach between the U.S. and the

European models, leading to a joint statement by ESO and NRAO to collaborate as equals on a single program. The baseline was an array of sixty-four 12-meter antennae located on a plateau at 5,000 meters in altitude near Atacama, Chile. In 1999, Japan joined the collaboration that produced what is now the Atacama Large Millimeter/Submillimeter Array (ALMA).

Shortly after VLT had achieved first light, ESO's Roberto Gilmozzi and a few colleagues approached Riccardo with plans to study the feasibility of a 100-meter diameter optical telescope, combining active and adaptive optics to obtain angular resolution on the ground that were even sharper than Hubble in space, with an area much larger than any other existing or then-planned optical telescope. Originally named the Overwhelmingly Large Telescope, Riccardo saw this project—now a 40-meter class telescope known as the Extremely Large Telescope—as an initiative for his successor at ESO. First light is currently projected for 2025.

NRAO, ALMA, and Associated Universities Incorporated

After the successful inauguration of VLT, Riccardo returned to Washington, D.C., in 1999, having been recruited to serve as president of Associated Universities Incorporated (AUI). On behalf of the National Science Foundation (NSF), AUI had managed the U.S. National Radio Astronomy Observatory (NRAO) since 1956 (and still does). NRAO operated three forefront radio facilities: the Robert C. Byrd Green Bank Telescope in West Virginia, the Very Large Array (VLA) in New Mexico, and the Very Long Baseline Array, comprising ten telescopes stretching across the United States. It also operated the Central Development Laboratory in Charlottesville, Virginia, which provided advanced technologies for radio telescopes around the world. When Riccardo arrived, NRAO was embarking on a major enhancement of the VLA: the creation of the Expanded Very Large Array (EVLA), to be carried out without stopping operations of the VLA. Significantly, AUI had also been named as the North American partner in the international ALMA project, and NRAO would be responsible for building nearly 40 percent of this more than $1 billion-dollar project. Riccardo saw an opportunity to continue his involvement with ALMA and perhaps, in this managerial role, to help the project with the growing pains he had foreseen as it was being formulated.

Riccardo's initial assessment was that NRAO telescopes provided high scientific return and that NRAO had established an advanced radio science technology base, while coping with serious funding limitations and organizational and management issues. Although the NSF provided required construction money for facilities, investment for maintenance and maximization of science capabilities was limited. Examples where support was needed included the development of data analysis and archive capabilities as well as for modernization of older and deployment of newer instruments. He saw the need for NRAO, AUI, and NSF to jointly establish priorities for upgrading facilities, providing better access to the larger community, and re-establishing competitive salaries for scientific staff.

In 1999, Riccardo viewed NRAO operating as a series of individual programs with a number of high-quality leaders, rather than as a single observatory. Given that ALMA would be even more challenging than the VLT, he saw the need for substantial reorganization in order to focus the existing technical skills so as to be able to draw from all of NRAO. He again established service to the community as the top priority, created opportunities to hire new scientists with a broad range of expertise, installed a new accounting system capable of tracking labor and material costs as well as scheduling progress, and centralized NRAO-wide purchasing and contracting services.

The construction of the new 100-meter Green Bank Telescope, which would replace the 300-foot telescope that collapsed in 1988, was substantially over budget and behind schedule. Given its strong political backing, Riccardo saw no option other than to complete the project as soon as possible. Thanks to heroic efforts by the NRAO/AUI team and support from Riccardo, science observations began in spring 2001 and routine operations were achieved in 2003.

With the 2001 approval to begin the transformation of the VLA into EVLA, the opportunity for the long-delayed VLA upgrades became a reality over the following decade, with a key step being the establishment of the EVLA as a new program carrying the required funding. The objectives were improving sensitivity by a factor of ten, complete coverage from 1 to 50 GHz, and enhanced spectral resolution. The plans included replacing wave-guide data transmission systems with fiber optics, installing new wide-band feeds for eight frequency bands, installing wide-band receivers at the base of feeds, implementing wireless detection and ranging correlators, and implementing a new back-end and data-archive system.

By 2001, as Japan ramped up its role in ALMA, it became clear that costs were growing, in part because of delays mandated by the ALMA governing board as well as delays in decisions regarding antenna procurement. Riccardo's assessment was that the project was technically sound, with three types of prototype antennas already built and tested, receivers and amplifiers under development, and good progress on the correlators.

He was also very positive about the software development, which involved all three major partners, with ESO taking the lead based on its VLT experience. The issues that were to dominate the next dozen years were not technical, but rather ones that involved managing an international collaboration that had no lead partner. ALMA remains not a legal entity in itself, but a partnership of three legal entities representing many countries in North America, Europe, and East Asia.

Riccardo was quite fascinated by the inter-continental collaborations on ALMA (North America, Europe, and East Asia, and sited in South America), which he saw as a potential future path for very large astronomy projects. At the same time, he was concerned about the level of cooperation that might be achievable given the complexities and political issues such arrangements might engender. Paraphrasing a former ALMA program manager, ALMA governance was an unstable equilibrium, held together by good will and hard work.

We are now two decades into the ALMA program—it has been successfully constructed and operates smoothly, producing cutting-edge science discoveries on a regular basis. It would be fascinating to hear from those involved over the course of the project to learn what has worked well and what might be done differently or better for future intercontinental partnerships. We can only speculate on what Riccardo's assessment and advice might be.

By 2001, Riccardo had recruited (again) one of us to join him at AUI. When he retired as president of AUI in 2004, Ethan Schreier was selected as his successor and remained AUI president for the next 13 years, overseeing the completion of both ALMA and the EVLA.

As president of AUI, Riccardo had played a leading role in negotiating the governance structure for ALMA and had initiated NRAO's transformation into a modern organization that could oversee the U.S. role in this immense project, while also carrying out the EVLA work. Before he retired in 2004, construction had been initiated on both EVLA and ALMA. Both have proven to be major successes and embody many of the innovations that Riccardo had introduced to astronomy through the years.

Over-Arching Thoughts

By the time he retired, Riccardo had established the discipline of X-ray astronomy, revolutionized both space- and ground-based optical astronomy, and greatly enhanced radio and millimeter wave astronomy. Just as important, he promoted a new way of approaching large science projects, ensuring his observatories were created by and for the science community, with cutting-edge research as their goal.

Before it became the norm, Riccardo consistently encouraged diversity. He strongly supported the first Women in Astronomy workshop, held at STScI, and conceived of the Baltimore Charter for Women in Astronomy. A number of women started their scientific careers as part of his X-ray group and even more did so at STScI. Several have proceeded to occupy some of the most senior positions in astronomy.

Riccardo always set future directions before he moved on: technology work for Chandra was underway when he left CfA; studies had been initiated for what became the James Webb Space Telescope before he left STScI; and the European Extremely Large Telescope and ALMA were being planned when he left ESO. He was able to work effectively and lead teams in a wide range of venues: industry, government/non-profit research centers, universities, institutes run by university or multi-national consortia, and management organizations. After his passing, his wife Mirella shared this perspective with one of us: "When things ran smoothly, Riccardo would get a little bored and start looking for a new challenge."

Clues to Riccardo's extraordinary success can be found throughout this memoir. Here we summarize some of our insights regarding his philosophy and guiding principles gleaned from our experiences working for, and truly collaborating with, Riccardo over the decades:

•Work at the limit of what can be conceived to ensure the maximum likelihood of obtaining critical results, while building within available resources.

•Don't merely accept small improvements in the existing state of the art if a major jump in sensitivity can be had through the use of new technologies.

•Keep instruments as simple as possible to obtain specific results, reducing costs and risk of total failure.

•Ensure useful science even with partial success through soft failure and redundancy.

•Hire the best available engineers, managers, programmers, etc., and work as an integrated team.

•Apply principles of systems engineering to science projects.

•Develop a common vision with staff.

•Encourage staff to balance research time along with service responsibilities.

Riccardo, while perceived by some as hard and aloof, developed strong bonds with those he worked closely with. He was intensely honest and personal, and insisted on honesty on the part of his colleagues. He could not tolerate people agreeing with him merely to gain his approval, but encouraged fierce debate, while working to gain consensus before a meeting was over. At a memorial symposium for Riccardo in May 2019, Jason Spyromilio shared a career-shaping interaction that took place within a few years of Riccardo's becoming director general at ESO. In a private meeting, Riccardo asked the then-thirty-year-old Spyromilio why work on the VLT and the parallel upgrade on ESO's NTT were behind schedule and over budget. The young astronomer began to answer in programmatic, bureaucratic terms, which led Riccardo to tell him twice that he was fired. When Spyromilio picked up his notebook and jacket to leave, Riccardo asked him where he was going. Spyromilio replied that he had been fired (twice) so he was leaving. Riccardo sensed that there was an opportunity there that should not be missed, so his response was to ask Spyromilio to sit back down and to share what he really thought was needed on the projects. As Riccardo himself reported:

> *"the complete upgrading of the command and control system of the 3.6m NTT by using and testing the software developed for the VLT…was successfully done…under the leadership of Jason Spyromilio, a relatively young astronomer who was given complete authority and responsibility for this work, to his great amazement."*[10]

Riccardo's assessment of his scientific career can be understood from some of his own words in *Secrets of the Hoary Deep*:

•"While analyzing Uhuru data, I came to love discovery for its own sake."[11]

•"I felt my greatest contribution to the field could be to build great instruments available to the entire astronomical community and to operate them in such a way as to maximize the scientific returns."[11]

•"As a young man of 28, I had invented the X-ray telescope; at 31, I had discovered the first X-ray star, Sco X-1, and the XRB. The nature of the X-ray binaries had become clear with Uhuru, the satellite that also discovered the intergalactic plasmas in clusters. Einstein made the field of X-ray astronomy relevant to all astronomers. Thanks to Chandra, the nature of the XRB…had almost been solved by 2002."[12]

- "It seemed as if my scientific life has come full circle."[12]

When Riccardo retired from AUI in 2004, he retained his position at Johns Hopkins. He continued his career-spanning interest by analyzing Chandra and multi-wavelength data from deep exposures to understand the X-ray background radiation, while remaining active in writing and speaking about the future of astronomy. He spent his last several years with Mirella in La Jolla near their daughter, Anna, and her husband, Ed. His home proudly displayed paintings (copies of great masters' works) and woodworking that he had done for relaxation in his younger days.

Riccardo was elected to the National Academy of Sciences in 1971, before his fortieth birthday. He received the 1980 Franklin Institute Elliott Cresson Medal, the 1981 American Astronomical Society Dannie Heineman Prize for Astrophysics and Henry Norris Russell Lectureship, the 1981 Astronomical Society of the Pacific Bruce Medal, the 1982 Gold Medal of the Royal Astronomical Society, the 1987 Wolf Prize in Physics, and a 2003 National Medal of Science. In 2002 he was awarded a share of the Nobel Prize for Physics "for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources" (see Figure 5). This Nobel was shared with astrophysicists Raymond Davis Jr. and Masatoshi Koshiba, who were honored for their research on cosmic neutrinos.

Figure 5: Ethan Schreier, Herbert Gursky, Riccardo Giacconi, and Harvey Tananbaum (left-to-right) in Stockholm celebrating Riccardo's 2002 Nobel Prize. (Photo provided by Ethan Schreier and Janet Levine.)

In summing up his career, Riccardo said: "I am grateful to live in this heroic era of astronomy and to have been able to participate and contribute to its evolution."[12]

The legions of astronomers who have benefited from his contributions, vision, guidance, and friendship are grateful, too.

ACKNOWLEDGMENTS

Some of the material in this memoir appeared in a short retrospective written by the same three authors and published in the *Proceedings of the National Academy of Sciences* in June 2019. The authors have also benefited extensively from Riccardo's own words as written in *Secrets of the Hoary Deep*, described by him as "a personal history of modern astronomy" rather than an autobiography. We have also drawn from biographical information posted on the Nobel website in 2002.[4]

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