Stephen S. Murray (1944-2015)

It is difficult to capture the essence of an individual and of more than half-a-lifetime of friendship and collaboration in just a few pages. Here, we share a few professional highlights and vignettes about our dear friend and colleague Steve Murray who passed away unexpectedly this past August. Steve was a master builder, a craftsman, a hardware and software expert, a scientist with an inventive, eager and curious mind, and a treasured individual in both his professional and personal lives which of course were deeply intertwined.

Steve and *Uhuru*

Steve first "came to our attention" in the summer/fall of 1970 when the X-ray group under Riccardo Giacconi at American Science & Engineering (AS&E) was readying for launch of *Uhuru*, the first satellite dedicated to X-ray astronomy. Through his thesis adviser Robbie Vogt, along with Ed Stone and Gordon Garmire, all at Caltech, Steve learned that AS&E was seeking a scientist or two to join our team. He arrived in Cambridge for a job interview, met with a few individuals, and gave a talk, no doubt, about his thesis work which involved the physical processes affecting the propagation of solar flare protons in interplanetary space. The reason we say "no doubt" in the preceding statement is that only one of us (HT) had joined the team at that point, and as Steve was fond of reminding him at appropriate times, he (HT) had dozed through much of Steve's talk, leading Steve to think that he had little chance of being made an offer. In fact, the reality was just the opposite. Steve's expertise with instrumentation, computers, data analysis, and the like made him an instant "must hire" for the AS&E team. An offer was forthcoming and Steve accepted, arriving at AS&E in late December 1970, just a few weeks after *Uhuru* was successfully launched.

Steve immediately engaged in devising new algorithms, developing new software, fixing bugs in existing code, and becoming an expert X-ray astronomer as quickly as possible. His early interests with *Uhuru* included mysterious high galactic latitude sources that were dubbed possible X-ray galaxies, extended emission from clusters of galaxies, source number counts versus flux, and the distribution of the sources on the sky. A particular focus both early on and throughout his career involved surveys and catalogs of sources. Surveys and catalogs with telescopes such as *Chandra* can be challenging, even with arcsecond resolution and precise positions. However, *Uhuru* was not a telescope; it scanned a swath on the sky with proportional counters peering through mechanical collimators. As the detectors traversed a source, a triangular shaped response was seen—with brighter sources for individual transits and with fainter sources only after summing together as many as 50-100 transits obtained over a day. The height of the collimators limited the field in the vertical direction to 10 degrees, while the azimuthal response was either 1 or 10 degrees across, depending on which counters and collimators made the observation. Figure 1 is a map showing lines of position on an equal area sky projection in galactic coordinates. The data were accumulated over ~70 days, covering close to 50% of the sky. The map shows 1171 lines of position. Even for Steve, it was a challenge to unravel all of these lines and determine the locations and intensities of the sources that produced them.

Sometimes, a bright source was detected on two nearly orthogonal scans leading to a crossing with high confidence of detection and a rather precise source location. In complex cases, many lines of positions possibly associated with multiple sources crisscrossed in a given region. Steve developed a maximum likelihood type approach, calculating for each point near a possible source the differential probability that a source at that location produced a given line of position. He

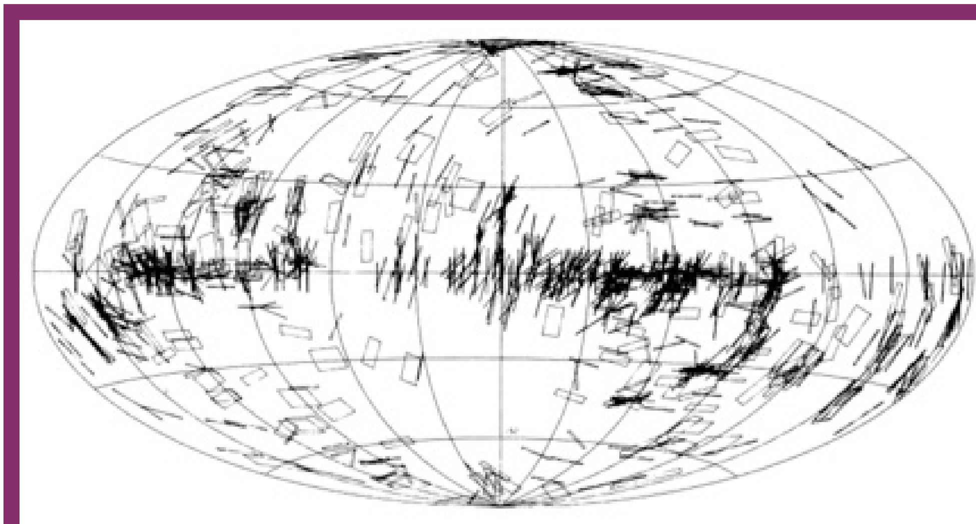

Figure 1: Lines of position (1171) which result from computer scans of superposed data are plotted on an equal area projection of the sky in Galactic coordinates. The line widths are ± 1σ wide (adapted from Giacconi, Murray, et al. 1972, ApJ, 178, 281).

then computed the product of the 1-d calculations for all of the relevant lines of position and thereby determined the joint probability density distribution for all of the points in a given region. The point with the maximum probability density was the most likely source location, and integration over regions bounded by iso-probability density contours then determined a 90% confidence region for the source location.

We (Steve and HT) produced an initial version of this catalog for an invited talk Riccardo was giving at the Dec 1971 AAS meeting in San Juan, Puerto Rico. Working long days and ending with an "all-nighter", we finally produced a catalog and taped the all-sky map to the inside of the glass door of the AS&E building for our colleagues to see as they arrived at work. We headed home to catch a few winks and to pack for the AAS meeting. One of the keys to being able to complete our work was Steve's ability to convince the company's computer managers to turn the usually batch-operated system over to us for a couple of days, so that we would have full use of the system to wring out bugs, verify software, and then produce the catalog. The resulting catalog was ultimately published as the 2U catalog with Giacconi, the PI of the mission as first author, and Murray, the catalog guru, as the 2nd author, along with several other team members as co-authors.

Steve and the *Einstein* Observatory

In the mid-70's Steve's interests turned back to instrumentation—or was he also responding to cries for help from our X-ray group which had moved from AS&E to the Smithsonian Astrophysical Observatory in July 1973 as part of the creation of the Harvard-Smithsonian Center for Astrophysics? Our team had been selected to lead the 2nd High Energy Astronomy Observatory mission which was renamed the *Einstein Observatory* following launch in 1978. With responsibilities for the scientific oversight of the X-ray telescope and for the design and construction of the two imaging instruments, we regularly broke new ground as the mission development proceeded.

If Technology Readiness Levels (TRLs) existed in the 70's, they were not applied with the rigor or enthusiasm often seen today. In simpler terms, this meant that our expert on telescopes, Leon Van Speybroeck worked closely with NASA and industry to figure out how to meet the specifications for the mirrors, and our team building the high resolution (arc second scale) imaging detectors needed an infusion of Steve and his expertise to help work through several technical challenges. With help also from Kenneth Pounds and Kenton Evans at Leicester U in the UK, we decided on a crossed grid charge detector to read out the micro-channel plates that detected the X-rays focused by the telescope. The detector required an evenly spaced grid of wires wound 128 wires to the inch. Steve developed an innovative technique, working with Harvard undergraduate Priscilla Cushman (now a professor at U. Minnesota involved in dark matter detection) as a summer student. They wound a double strand of wires and then unwound one strand to produce an evenly spaced grid in one direction, and then they repeated

Figure 2: Steve demonstrating the prototype for the Einstein HRI (courtesy Karen Tucker).

the step and oriented a second grid at 90 degrees to the first to produce a working 2-dimensional readout.

Quoted in the Star Splitters written by Wallace Tucker to describe the HEAO program, Steve said: "We just kept trying things until something worked. We really played the basement inventors. It took a few years, but after going down many blind alleys, finally we succeeded. In the end it turned out that the simplest ways were the ways that worked."

Steve and ROSAT

Following the successful *Einstein* program, Steve was selected as the lead to provide a High Resolution Imager for the German-led ROSAT satellite. Along with Martin Zombeck and others, Steve upgraded the HRI using CsI coatings to achieve a higher quantum efficiency. After the ROSAT All-Sky Survey was completed, the HRI was used in pointed mode to obtain the highest quality ROSAT images. When the proportional counter detectors exhausted their gas supply, the HRI served as the only ROSAT detector for several years of extended operations.

Steve and *Chandra*

Steve was competitively selected as principal investigator for the *Chandra* High Resolution Camera (HRC) in the mid-1980's. As PI, Steve was fully engaged in all aspects of the design, construction, calibration, integration, and orbital activation of the flight instrument. His direct, steady leadership throughout the entire project was the single most important reason why HRC continues to function well to this day, nearly 17 years after launch. Notwithstanding the hard work and long hours, Steve thoroughly enjoyed all aspects of the construction and development of the HRC. He was equally at home meeting with high-level NASA administrators, writing C code to analyze his data, or tightening screws on a vacuum pipe for sub-assembly testing. He also demanded a high standard of work from himself and those around him. Along with Jon Chappell and Gerry Austin, Steve personally led the flight assembly of the MCP stacks and UV/Ion shields onto the crossed-grid readouts, spending many long hours in the cleanroom to ensure that all the work was done completely and carefully. This level of personal engagement, dedication, and broad competence for a large project serves as an example to the following generation of scientists who will be building the future space observatories. In 2000, Steve received the NASA Exceptional Service Medal in recognition of his work on the *Chandra* HRC.

Steve's principal scientific interests with *Chandra* were X-ray AGN surveys and high timing resolution, and he made important discoveries in these areas. The high spatial and temporal resolution of the *Chandra* HRC clearly separated the emission of the central point source in the PWN 3C 58 from the diffuse nebula, and detected millisecond pulsations from this source (Murray et al. 2002, ApJ, 568, 226). Deep observations of this central point source with the ACIS instrument put strong upper limits on the thermal emission from the central neutron star that were well below the predictions of standard cooling models, suggesting the presence of some exotic cooling mechanism in the neutron star interior (Slane et al. 2002, ApJ, 571, L45). Steve was also heavily involved in the *Chandra* AGN surveys of the DEEP2 and Boötes fields, contributing a significant fraction of the HRC Guaranteed Time Observations (GTO) time to ensure complete X-ray coverage in support of the large multi-wavelength campaigns.

Steve was committed to carrying out the best science with *Chandra*. In addition to those who helped him write the winning proposal and those involved in building the HRC, Steve included "new-comers" who brought along great science ideas. He focused the HRC GTO program on the best and most exciting science, with targets ranging from planets in our Solar system; to stars, supernova remnants, and globular clusters in our Milky Way; to galaxies including Andromeda and elliptical galaxies with hot gas haloes and supermassive black holes in their cores; and to samples of clusters of galaxies that produced new constraints on cosmological constants by measuring cluster growth over cosmological times. Steve often used some of his GTO time to kick-start new projects. These included the first *Chandra* observations of the Bullet Cluster, the initial *Chandra* deep observations of the cluster outskirts of A133, and the beginning of the large X-ray surveys of galaxy clusters detected through the Sunyaev-Zeldovich effect by both the South Pole Telescope and ESA's Planck mission, which later both led to *Chandra* X-ray Visionary Project programs.

The Boötes Survey was perhaps closest to Steve's heart. Boötes combined Steve's HRC GTO observations with *Chandra* GO proposals to survey a 9 square degree region, still the largest *Chandra* contiguous survey. Although the initial *Chandra* observations were short (only 5 ksec), deeper observations followed. The Boötes survey resulted in the detection of thousands of AGN and several tens of groups and clusters of galax-

Figure 3: Steve in the lab with the Chandra High Resolution Camera

ies. Three key results from these surveys include:

(1) radio AGN are primarily found in luminous red sequence galaxies, are strongly clustered, and have very low Eddington ratios; X-ray selected AGN are found in "green valley" galaxies, are less clustered, and have higher accretion rates; and IR AGN reside in slightly bluer, less luminous galaxies than X-ray AGN, are weakly clustered, and have higher accretion rates than X-ray or radio AGN (Hickox et al. 2009, ApJ, 696, 891);

(2) based on a sample of more than 330,000 galaxies, radio AGN are, in general, undergoing radiatively inefficient accretion in passive galaxies, while X-ray and IR selected AGN are more radiatively efficient and found in star-forming galaxies, with the galaxy populations of these two AGN types remaining distinct over the last 9 Gyr (Goulding et al. 2014, ApJ, 783, 40);

(3) quasar obscuration is associated with dust enshrouded starburst galaxies (Chen et al. 2015, ApJ, 802, 50).

There are many dozens of publications in the refereed literature that make use of these data, which will continue to be a resource for years to come. Coupled with optical spectroscopy, these observations showed that AGN also map the large-scale structures traced by galaxies. Ground-based MMT-Hectospec observations of the Boötes sources have been invaluable for source detections. Steve was looking forward to MMT-Binospec observations for sources too faint for Hectospec.

Steve as Administrator and Teacher

Steve also became Associate Director (AD) for CfA's High Energy Astrophysics Division (HEAD) for about a decade (1992-2003) when Harvey Tananbaum stepped down to become the Director of the *Chandra* X-ray Center (CXC). Steve worked tirelessly to ensure that the unusual organizational structure, with the CXC inside HEAD, actually worked successfully. Alongside the exponential growth of the CXC, Steve maintained the integrity of HEAD and understood the value and synergies of the complex merger. He worked to combine the existing administrative and support structures of HEAD with those being developed for the CXC. To this day, the model that he promoted has allowed the CXC to draw on the resources of HEAD and CfA, while the CXC supports the entire astronomical community in its use of *Chandra*.

While still serving as HRC PI and after a decade as HEAD AD, Steve sought new avenues for his hardware bent. In 2003-2004 he spent a semester as a visiting professor at MIT where he created and taught a course entitled "Proposal Writing for Small NASA Missions." His thoughts were that students needed to know more than how to design or build a mission. They also needed to be able to articulate the rationale for doing a new mission; to lay out a technical approach, schedule, and budget; and to convince others that the mission was compelling and feasible.

After Charles Alcock became CfA Director, Steve and he jointly established a new administrative role for Steve as SAO Deputy Director for Science (2005-2009). Steve was devoted to the collaborative endeavor that is the Harvard-Smithsonian Center for Astrophysics. He developed a comprehensive knowledge across the breadth of SAO science. He supported the development of budgets, coordinated hiring of a new cadre of scientists, and was a key organizer of the CfA Strategic Plan. During his tenure as Deputy Director for Science, he contributed his analytic skills to setting priorities at the Observatory and guided administrative and programmatic efforts in the Director's Office.

Steve moved to Baltimore in 2010 to join his wife Kathryn Flanagan (JWST Mission HEAD, Deputy Director STScI, Interim Director STScI). In Baltimore, Steve served as a Research Professor at JHU (2010-2015), a Visiting Researcher at JHU-APL (2010-2012) and a Senior Research Astronomer at STScI (2013-2015). At JHU, Steve (with Warren Moos) developed and taught the "Introduction to Space Science and Technology" the keystone course in the JHU minor "Space Science and Engineering". At Steve's urging, the course emphasized the design of science mission concepts by the students. Although restricted to upper level undergraduates in the sciences and engineering, the course was quite popular and each year reached its enrollment maximum shortly after registration opened. Looking for a more "hands-on" way to get undergraduates involved in spaceflight missions, Steve began the design of a CubeSat teaching laboratory utilizing funding for new teaching concepts from the Office of the Provost. During the fall of 2014, with a group of undergraduates he began testing CubeSat design tools with the plan to have future undergraduate students design and prepare flight satellites.

Steve and ADS

Throughout his moves and changing job descriptions, Steve led the Astrophysics Data System as PI (beginning in 1991/1992), forming a small, elite team supported by NASA. The ADS team revolutionized access to the astrophysics literature by providing free, open digital access to the entire astronomical archive of all major (and nearly all minor) astronomical journals back to their first publication (some into the early 1800's). The ADS corpus presently consists of 11 million bibliographic records, 85 million citations, and close to 4.5 million full-text documents, the world's most complete collection of scholarly content in the physical sciences. The 2002 Harvard-Smithsonian Visiting Committee reported "It is no exaggeration to say that ADS has revolutionized the use of the astronomical literature, dramatically changed the use and focus of astronomical libraries, empowered astronomy research in underdeveloped countries and small institutions, and is probably the most valuable single contribution to astronomy research that the CfA has made in its lifetime."

Steve and Future Missions

Steve also devoted a significant fraction of his energy to developing new mission concepts. In particular, he played a central role in the development and evolution of the Wide Field X-ray Telescope (WFXT) and Whipple concepts. The WFXT concept is an X-ray telescope with a large effective area and field of view intended for a deep survey of the extragalactic sky. The primary goals of this mission are to detect clusters with $M>10^{14}\,M_\odot$ to z~2 in the surveyed region and to map the distribution of AGN to z~5, ultimately to place unprecedented constraints on the formation and evolution of supermassive black holes (SMBH) and the relationship between SMBHs and their host galaxies. Demonstrating Steve's technical skill and versatility, the Whipple mission concept is a space-based optical observatory to continuously monitor the light curves of tens of thousands of stars at 20 Hz cadence to search for occultations by Kuiper Belt and Oort Cloud objects. The ultimate goal of this mission is to constrain dynamical models of the evolution of the early Solar system. If either or both of these are ultimately funded to flight, the community will owe a further debt to Steve and his ability to define and refine these concepts into state of the art astronomical observatories.

Steve's Legacy

Steve has served the community with his unparalleled expertise spanning hardware, technology, and science. Riccardo Giacconi was keenly aware of Steve's unique combination of skills dating back to the development of the 2U catalog and through his work to develop an all-electronic, high-resolution imaging detector for the *Einstein Observatory*. Upon learning of Steve's passing, Riccardo wrote: "Steve and I were very close during the period when we stayed at JHU. We could talk of all aspects of science and express our ideas and our disappointments. He was a very good man and I feel a great loss." Recently Riccardo added: "At JHU, Steve and I discussed at length what we came to call 'Science Systems Engineering', which we summarized with a simple mnemonic: Learn-Think-Plan-Do-and Teach. (Giacconi, R., 2013, Considerations on X-ray Astronomy (Appendix A), Mem. S. A. It., 84, 472). Steve was sharing this philosophy and approach to science with his students at JHU."

Steve's legacy continues through the ADS, *Chandra*, and in other software platforms that our community uses every day. Perhaps as importantly, Steve's legacy resides in the colleagues, co-workers, and students who were fortunate enough to work with him. His lifetime of commitment to research, innovation, teaching, and outreach serves as a model and inspiration for us all. To honor Steve's contributions, the *Chandra* HRC project has initiated a Distinguished Lecturer series in Steve's name. As Steve would have demanded, these lectures are promptly posted for public access (see Stephen Murray Distinguished Lectures at *https://www.youtube.com/channel/UCMFEeX24_lviXNhek5-FFLA*) and serve as a constant reminder of the extraordinary breadth and superb quality of Steve's scientific interests. ■

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