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WILLIAM LESTER KRAUSHAAR
1920–2008

A Biographical Memoir by

DAN MCCAMMON AND GEORGE W. CLARK

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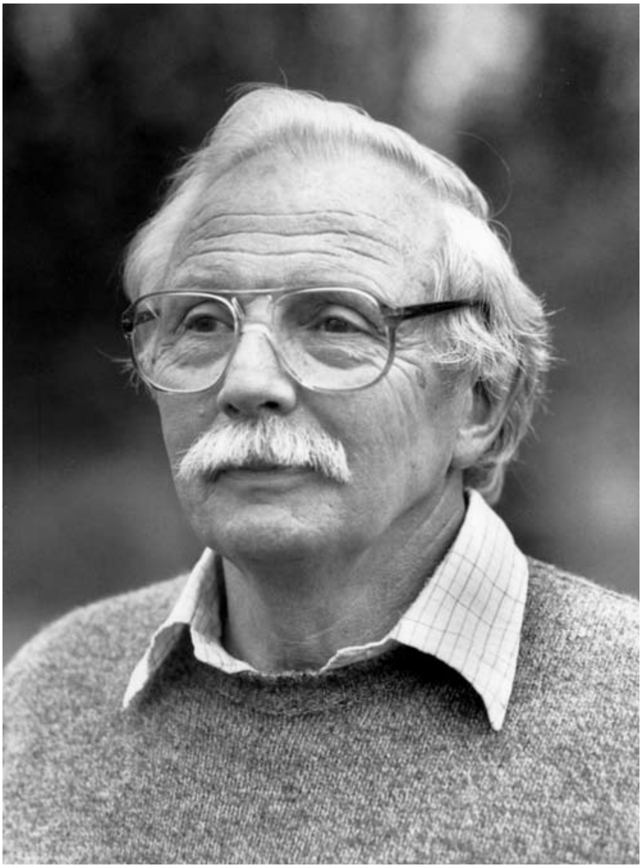
Biographical Memoir



Photograph by Andrew Kraushaar

William L Kraushaar

WILLIAM LESTER KRAUSHAAR

April 1, 1920–March 21, 2008

BY DAN MCCAMMON AND GEORGE W. CLARK

William Lester Kraushaar was the founder of high-energy gamma-ray astronomy, and a leader in the development of soft X-ray astronomy and its application to exploration of the interstellar medium. At Cornell and then at MIT he worked on particle and cosmic-ray physics, and then led the 10-year effort that discovered the galactic and extragalactic components of high-energy cosmic gamma rays. Later, at the University of Wisconsin he created and led the X-ray astronomy group that played a key role in the discovery and characterization of the hot phases of the interstellar medium. His students and associates benefited profoundly from his gentle guidance and firm leadership, and fondly remember his quiet example of how science should be done. In retirement he lived in Maine, where he died on March 21, 2008, a few days before his 88th birthday.

EARLY YEARS

William Lester Kraushaar was born in Newark, New Jersey, on April 1, 1920, to Lester A. Kraushaar and Helen Osterhoudt Kraushaar. William's brother, Jack, who became a nuclear physicist at the University of Colorado, was born three years later, the year the family moved to Maplewood, New Jersey. Their father was a trust officer of the Chase Manhattan Bank on Broad Street in New York.

William Kraushaar characterized his earliest science projects as rather undisciplined experiments with a birthday chemistry set, old crystal and battery-operated radio receivers, and small bombs made and exploded in the family basement. At age 12 he became interested in amateur radio and soon passed the tests for an operator's license. Upon receiving his call letters (W2IHK), he put together his own transmitter and went on the air. This early experience with radio laid a foundation for his later interest in experimental science and physics and his particular flair for electronics.

Kraushaar attended Columbia High School in Maplewood where more than half of its graduates went on to college. Most of the science faculty had doctoral degrees and were happy to have jobs as high school teachers during the Great Depression. Kraushaar was the state champion in high hurdles in his senior year. He also developed a lifelong interest in classical music, and became proficient on the clarinet and oboe. During his years at MIT, he played with an amateur symphony orchestra in Concord, Massachusetts.

COLLEGE AND THE WAR YEARS

In 1938 Kraushaar entered Lafayette College in Easton, Pennsylvania. A year of college physics, chemistry, calculus, and electrical engineering convinced him that physics, and not engineering, chemistry, amateur radio, or bombs warranted further study. He was elected to Phi Beta Kappa in his senior year and graduated with a B.Sc. in physics in 1942. Soon after receiving his degree, he married Margaret ("Maggie") Freidinger. They had met when Maggie was attending Western Reserve University in Cleveland, and Kraushaar had often hitchhiked to spend the weekend. With World War II in full force Kraushaar was recruited to the National Bureau of Standards in Washington, D.C., where the couple set up housekeeping in an apartment near NBS.

Work was underway at NBS on development of the proximity-fused artillery shells that were perfected and deployed in late 1944. The shells made a major contribution to the defeat of Germany on the Western Front, and were considered to be among the most important military developments of the war. One of Kraushaar's duties at NBS required him to travel by train to the Aberdeen Proving Ground in Maryland with a briefcase packed with samples of fused shells for testing. Many years later when a student complained about a certain tedious task of statistical data analysis, Kraushaar recounted how such a study had solved a critical problem of sporadic failures encountered during test firings over a beach on the shore of Chesapeake Bay. An exhaustive statistical analysis of possible causes showed the only correlation was between times of failure and the phases of the moon. That weird result, at first derided, was the key to identifying the true cause: a variation in the position of the wet-dry boundary along the beach during high spring tides. The shells were fused to detonate when a reflected radio signal indicated proximity to the target. The cause of failure turned out to be reflections of the radio signals from the moveable wet-dry boundary.

At the end of the war Kraushaar entered the graduate program in physics at Cornell University and joined the cosmic-ray group of Kenneth Greisen. The couple's first child, Mark, was born in 1945, and in September of that year they moved to a small house in Ithaca, New York.

COSMIC-RAY AND PARTICLE PHYSICS

In the summer of 1948 Greisen's group set up experiments at 14,000 feet on Mt. Evans in Colorado, renewing the investigations of cosmic-ray muons in which Greisen, as the first Ph.D. student of Bruno Rossi in America, had been engaged at Cornell before the war. Both Greisen and Rossi had worked on the bomb at Los Alamos. After the war Rossi went to MIT, and Greisen returned to Cornell. Kraushaar's principal responsibility in the new experiments was to prepare the electronics, which he did with a prowess that earned him the nickname "blocking-oscillator Bill." His thesis research produced a definitive measurement of the range spectrum of low-energy muons that proved the dominant source of electrons in cosmic rays is electron-photon cascades and not muon decays (1949).

Kraushaar received his Ph.D. in 1949. In that same year daughter Sunna was born, and he was appointed research associate in the cosmic-ray group that Rossi had established at MIT for research in cosmic rays and particle physics. The Kraushaar family moved to the Boston area, and soon acquired a house in the Conantum residential housing development in Concord, Massachusetts, a development designed especially for young couples by MIT Professor Carl Koch. Each house was on a one-acre plot with a share in 60 acres of common park land. Many of their neighbors and lifelong friends were academics at Harvard and MIT who commuted to work along the ever busier Route 2. In 1953 the Kraushaar's second son, Andrew, was born.

When Kraushaar arrived at MIT, the 350 MeV electron synchrotron was in its final stage of development. He soon became expert in the technology of particle accelerators (Thomas et al., 1952), and together with Matthew Sands helped to put the finishing touches on what was one of the earliest accelerators capable of creating pions. His first project was to prepare a beam of positive pions and measure their mean life. From an observation of the decay of 57 pions in a crystal of stilbene, employing an ultrafast distributed amplifier of his own design, he obtained a value of

(1.65 ± 0.33) × 10^{-8} seconds (Kraushaar et al., 1950). In a refined version of the experiment with 670 selected decay events in a xylene-terphenyl liquid scintillation counter, he obtained a value of (2.53 ± 0.10) × 10^{-8} seconds (1952), in agreement with other results. During this time, he also carried out a theoretical study of high-energy nucleon-nucleon collisions with L. J. Marks (1954), and an experiment on the photoproduction of positive pions with G. S. Janes (1954).

Kraushaar next joined a project initiated by Rossi for the purpose of finding clues to the origin of the highest-energy cosmic rays through measurements of the extensive particle showers they generate in the atmosphere. The idea was to construct a wide array of detectors with which one could measure the arrival directions and sizes of the particle showers by the novel methods of density sampling (Williams, 1948) and fast timing (Bassi et al., 1953). The recently reported and inexpensive liquid organic scintillators made feasible the construction of detectors with large sensitive areas and capable of both fast timing and particle density measurements.

In the new project Kraushaar took the major responsibility for development of the electronic data system that recorded photographically the detector responses displayed on a bank of oscilloscopes. With Frank Scherb, then a graduate student, he optimized the array design by use of a simple analog computer that he devised and assembled on a wooden frame with weighted lengths of fishing line and crimped bits of solder. The efficacy of a trial array was judged by the accuracy with which the specified core location and size of a test shower could be recovered from the particle densities calculated at the various detectors and put into the computer. With this device he and Scherb evaluated the relative merits of various configurations of the detector array and set the design accordingly.

With plans for the experiment largely complete, and its location at the Agassiz Station of the Harvard Observatory settled, Kraushaar took a leave of absence from MIT to spend a year as a Fulbright research scholar in Japan, where he took his family for the academic year 1954-1955. The idea for the trip arose in conversations with Minoru Oda, who had participated as a visitor in the early stages of the Agassiz experiment. In Japan Kraushaar joined the cosmic-ray research group at Osaka City University, where Oda was a professor. The group was headed by Prof. Yuzuru Watase who was also head of the cosmic-ray research laboratory at Osaka University.

Japan's cyclotron accelerators had been dismantled and dumped into the sea by U.S. occupying forces following the war, so Watase and other high-energy physicists had taken up cosmic-ray research. An underground cloud chamber experiment was underway that had apparently detected anomalous nuclear interactions caused by energetic particles that traversed the chamber and were presumed to be muons. The results appeared to indicate that the muon had properties inconsistent with the new idea that it was, in effect, a "heavy electron." Kraushaar, suspecting contamination by other particles, assisted graduate student Yojiro Murata in modifying the cloud chamber-triggering logic by the addition of a delayed coincidence circuit constructed with parts from discarded military electronic equipment, which were all that was available to the Japanese researchers. This modification limited the cloud chamber expansions to events in which a particle that stopped in the detector below the chamber decayed like a muon within a few microseconds with the ejection of an energetic electron. With that modification the anomalous effect disappeared (Fukui et al., 1958, 1959).

During his time in Japan Kraushaar published two papers on the magnetic field in the solar system and its effects on the propagation of solar cosmic rays and their impact on Earth (Kraushaar, 1955a,b). Some of the graduate students from these cosmic-ray groups, including Yasuo Tanaka and Sigenori Miyamoto, later joined forces with Minoru Oda to establish the X-ray astronomy program at the Institute for Space and Aeronautical Science, which maintained close ties to the X-ray astronomy group that Kraushaar later established at the University of Wisconsin.

When he returned to MIT, Kraushaar found preparations for the Agassiz experiment nearly finished. Operations began under his direction in August 1955. Within a few days, during a rainstorm, one of the detectors filled with flammable liquid scintillator was struck by lightning and set ablaze. After several months and tense negotiations between Harvard and MIT, operations resumed, first with fireproofed tanks of liquid scintillator, and then with large nonflammable disks of plastic scintillator manufactured at MIT. The Agassiz experiment (Clark et al., 1961) measured the structure and size spectrum of giant cosmic-ray air showers and determined the energy spectrum and arrival directions of the primary particles up to energies of 10^{18} eV. No evidence was found of a high-energy cutoff in the energy spectrum of primary particles, and no statistically significant departure from isotropy in the distribution of their celestial arrival directions. The results deepened the mystery of the origin of the highest energy cosmic rays. The Agassiz experiment was the first of its kind, and the precursor of similar smaller and larger experiments carried out by MIT scientists in India, Bolivia, and New Mexico, and by numerous other groups around the world.

GAMMA-RAY ASTRONOMY

After the operational phase of the Agassiz experiment ended in 1957, Kraushaar initiated a decade of balloon and satellite experiments aimed at the detection of cosmic gamma rays. The first balloon experiment was aimed at detecting cosmic gamma rays in the energy range below 10 MeV. It yielded only discouraging evidence of an overwhelming problem of background interference generated by ordinary cosmic rays in the surrounding atmosphere and in the detector itself and the vehicle that carried it. Kraushaar therefore turned to what promised to be a more tractable problem of searching for higher-energy gamma rays.

With a balloon experiment in 1947 Robert Hulsizer, a student of Rossi, had set an upper limit of one percent on the proportion of high-energy gamma rays among other cosmic rays of the same energy (Hulsizer and Rossi, 1948). Nevertheless, there was no doubt that high-energy gamma rays are present in the primary radiation, since they certainly arise in the decay of neutral pions produced in the interactions of high-energy cosmic-ray protons with interstellar matter. Thus it was clear that if high-energy gamma rays could be observed they would provide interesting information about the distribution of matter and cosmic rays in the Galaxy and perhaps beyond.

The problem, as in the case of low-energy gamma rays, was the potential blizzard of locally produced background radiations. In this case, however, a practical solution seemed possible in the form of a combination of scintillation and Cerenkov counters that would be selectively responsive to gamma rays with energies greater than 50 MeV that arrive from directions within a restricted field of view and would be, at the same time, highly efficient in rejecting background events. Such a combination of counters could be called a "gamma-ray telescope," and the electronic signal it generated a "gamma-ray signature event." Convincing evidence that signature events were cosmic in origin would depend on obtaining a sufficient number to show with statistical certainty the expected concentration of their arrival directions toward the Milky Way where the interactions of cosmic rays with interstellar matter are concentrated.

In 1960 Kraushaar's student Thomas Cline carried out a balloon experiment with the first version of a gamma-ray telescope. As the balloon approached its highest altitude near 100,000 feet, the rate of gamma-ray signature events declined in proportion to the decrease in the residual thickness of atmosphere above in which background gamma rays were generated. An extrapolation of the measured rate to zero thickness of atmosphere was consistent within its statistical uncertainty with a finite intensity of cosmic gamma rays but also with zero intensity. So the final result could only be claimed as a new and much lower upper limit (Cline, 1961).

Meanwhile, the first opportunities arose for scientific experiments on satellites. This offered the prospect of an observation above the interfering atmosphere with duration sufficient to provide the necessary number of gamma-ray signature events. Kraushaar submitted a proposal to the new National Aeronautics and Space Administration for a high-energy gamma-ray telescope in orbit. It would be the first of two MIT satellite gamma-ray observatories. Its design was constrained by a weight limit under 100 pounds and a severe limit on power. High voltage had to be generated for the various stages of a large number of photomultiplier tubes. Kraushaar realized that the interface specifications allowed more power to be taken from the spacecraft clock signal than was available on the power bus. He devised a lightweight Cockcroft-Walton-style high-voltage generator driven by the spacecraft clock, with each photomultiplier dynode connected directly to the appropriate stage of the generator to avoid the usual power-sapping resistive divider.

Gordon Garmire, one of Kraushaar's Ph.D. students who worked closely with him on this experiment, remembers being impressed by his great care in testing everything that went into the experiment. He operated each photomultiplier in a black cloth bag, striking it many times with his hand while watching the noise level. Many tubes were rejected when this test disclosed small particles trapped in the tube during manufacturing. One of Garmire's assignments was to coat the outside of the phototubes with a conductive layer to reduce noise in the tube. Silver conducting paint proved unsatisfactory, and Kraushaar suggested using aquadag, a colloidal suspension of carbon. Garmire tried it but could not get the solution to wet the glass. Kraushaar remembered that if you wash a wine glass well enough, the water would wet the surface until it evaporated. After cleaning the tube thoroughly, sure enough, the aquadag coated the glass beautifully.

Seven units for testing and backup were fabricated in the cosmic-ray laboratory at MIT. One unit was tested to destruction on an industrial "shake table," bringing to light a critical structural flaw that Kraushaar fixed with his own vibration engineering. Four attempts to test another unit in balloon flights were unsuccessful on account of balloon failures, the last of which resulted in the unit's destruction. One unit was calibrated in the beam of gamma rays produced at the MIT synchrotron and later in the "tagged" gamma-ray beam at the Caltech synchrotron. At Cape Canaveral the flight unit was in the final stages of prelaunch checkout with strong pressure to maintain the schedule when Kraushaar discovered a fault in the Sun sensor for orientation determination in orbit. With his typical tact and firmness he managed to halt the countdown for several days until the problem was fixed. The experiment was finally launched on April 27, 1961, as

Explorer XI, the first orbiting astronomical observatory of any kind.

Explorer XI was placed into an elliptical orbit with an apogee much higher than planned, which carried it periodically through the Van Allen Belt of trapped radiation. In seven months of orbital operation only 141 hours were culled as useful observing time due primarily to time lost when the counters were jammed by trapped radiation, and early failure of the spacecraft tape recorder, which restricted data reception to times within sight of a NASA receiving station. Only 31 gamma-ray signature events were recorded when the field of view was above Earth's bright horizon, a number too small to show a statistically significant concentration of arrival directions toward the galactic equator. Lacking that essential proof of their cosmic origin, the result was claimed to be only a new upper limit on the cosmic gamma-ray intensity (Kraushaar et al., 1965).

During the postflight refurbishment and calibration of the backup flight unit and analysis of the flight data, Kraushaar and Garmire published a review of the theoretical prospects for gamma-ray astronomy based on the latest information about the distribution of cosmic rays and interstellar matter in the Galaxy, and the physical processes by which gamma rays are produced (Garmire and Kraushaar, 1965).

Soon after the limitations of the data from Explorer XI became apparent, Kraushaar initiated a new project to place an improved gamma-ray telescope in the wheel section of an Orbiting Solar Observatory (OSO). The improvements included, aside from more compact and durable electronics, a multilayer scintillation-counter calorimeter placed below the Cerenkov counter to absorb the electron pairs generated by incident gamma rays and measure their energies, and an anticoincidence shield that surrounded the entire telescope. In the new project Kraushaar abandoned the cottage-industry style of the Explorer XI telescope construction, and enlisted the engineering capabilities of the Lincoln Laboratories, an organization with wide experience in space technology that was managed by MIT for the Defense Department. The new telescope was first launched in August 1965 aboard OSO-C, which failed to achieve orbit.

With preparations underway for another attempt to launch the OSO instrument, an opportunity arose to fly the backup unit of the Explorer XI telescope on the first Orbiting Astronomical Observatory (OAO). The refurbished instrument was launched in April 1966 on OAO-1, which suffered a fatal system failure after three days in orbit and yielded no useful gamma-ray data.

Finally, the backup unit of the second MIT gamma-ray telescope was launched on OSO-3 on March 8, 1967. It operated for 16 months and registered 621 gamma-ray signature events attributable to cosmic gamma rays with energies greater than 50 MeV. The arrival directions at galactic latitudes less than 40 degrees were clearly concentrated toward the Milky Way with maximum intensity around the center of the Galaxy. Above 40 degrees the gamma-ray signature events showed evidence of their extragalactic origin in the isotropic distribution of their celestial arrival directions, their different spectral distribution, and the lack of variation in their rate with the intensity of background-generating cosmic rays as the satellite moved in geomagnetic latitude. Thus the MIT experiment on OSO-3 yielded the first all-sky map of high-energy gamma rays, and discovered their galactic and extragalactic components. The results inaugurated the new field of gamma-ray astronomy (Clark et al., 1968; Kraushaar et al., 1972).

Throughout his years at MIT Kraushaar taught undergraduate physics and guided the research of graduate students, of whom several went on to play leading roles in space research. He and his colleague Uno Ingard wrote a textbook entitled *Introduction to Mechanics, Matter, and Waves* (1960). As aptly described on the book jacket, freshman physics was presented in a way that "enables the student to observe and appreciate the vital role of experiment and prevents him from obtaining the erroneous picture of physics as a complete deductive package, which often a course in mechanics tends to give."

SOFT X-RAY ASTRONOMY

In 1965 Kraushaar moved to the University of Wisconsin in Madison along with Frank Scherb to establish a space physics group within the physics department. Scherb pursued his interests in solar system plasmas along the lines of research in which he had become engaged at MIT after completing his Ph.D. thesis on air showers. Kraushaar plunged into the even newer field of X-ray astronomy. In his gamma-ray work Kraushaar had been impressed with how little was known about the properties of the interstellar medium (ISM). He realized that observations of diffuse X rays with energies less than 1 keV, so-called "soft X rays," that are strongly absorbed by matter could provide interesting new information about the properties of the ISM.

Aside from the appeal of a new area of research where nearly everything observed was unpredicted and mysterious, the special attraction of X-ray astronomy for Kraushaar was that the typical flux of celestial X rays is orders of magnitude larger than that of gamma rays. The next generation of gamma-ray experiments would clearly require very large, expensive, and new kinds of instruments developed in big laboratories and industry, leaving little opportunity for trial-and-error experimentation by graduate students. To be sure, observations of soft X rays would require the development of new detectors and ultimately satellite experiments. But small instruments carried on relatively inexpensive suborbital "sounding rocket" flights lasting only a few minutes could collect thousands of X-ray photons. This made possible a viable program in which instruments were developed entirely within a modest university laboratory in the sort of hands-on experimental project that Kraushaar most enjoyed.

Before 1965, observations had been limited to X rays with energies above 2 keV whose interactions with interstellar matter are relatively weak. But X-ray absorption increases rapidly with decreasing energy. If instrumentation could be developed to detect X rays in the energy range 0.1-1.0 keV, an all-sky map of soft X rays would be in effect an X-ray picture of the ISM, providing information on its distribution and properties. To that end Kraushaar initiated a program to develop multiwire counters with separate volumes for soft X-ray detection and anticoincidence background suppression. Such detectors would provide major improvements in weight and area efficiency over banks of individual counters that had been used previously to achieve large sensitive areas. Achieving efficient response for soft X rays was more difficult. Beryllium windows could not yet be made thin enough, and the previously used 6.5 μm Mylar film was less than ideal. Kraushaar's group was the first to fly counters with 3.2 μm Mylar and the even more fragile 2 μm polycarbonate film that had just become commercially available.

Later experiments used Formvar and polycarbonate membranes as thin as 0.1 μm produced by casting on water. All such films had to be supported by metal mesh to withstand the pressure of the filling gas during the vibration and acoustic pressure of a rocket launch and the vacuum of space. And since filling gas diffused through the films, an onboard supply of gas with a system of electronic sensors and valves was required to maintain the gas density constant for accurate measurement of X-ray energies. Postdoc Alan

Bunner, a recent student of Ken Greisen, was a significant early addition to the group. He stayed on for 12 years as Kraushaar's right-hand man in the laboratory, playing a key role in most of these technical developments and managing two satellite experiments. During Kraushaar's first four years at Wisconsin, Bunner, Kraushaar, and his graduate students built and flew five continually improved payloads on unguided spinning rockets to map the intensity of the diffuse soft X rays. The detector on such a rocket recorded whatever passed through its field of view, resulting in an observation well suited to mapping diffuse soft X rays.

In 1968 Bowyer, Field, and Mack reported the first successful detection of diffuse soft X rays (Bowyer et al., 1968). To everyone's surprise the observed intensity at energies near 250 eV was much higher than expected from an extrapolation of the intensities found at higher energies with allowance for interstellar absorption. Diffuse soft X rays apparently came from a previously unknown source. It was soon ascribed to hot, dense intergalactic plasma at a temperature near 1 million degrees and a density sufficient to slow and eventually reverse expansion of the Universe. Such an intergalactic medium would fill the gap left by the visible stars and galaxies whose combined mass density adds up to only 0.5 percent of the amount required to reverse cosmological expansion. This pleased some cosmologists who disliked the idea of a Universe born once and expanding forever. They preferred an eternal cycle of big bangs and big crunches. And 1 million degrees fits nicely between two temperature limits set by other observations on the temperature of such a medium. It had to be hotter than 2×10^5 K to be sufficiently ionized to be transparent to light from distant highly red-shifted galaxies. It had to be colder than 3×10^6 K to avoid making the X-ray background above 2 keV brighter than observed.

Rocket experiments by Wisconsin (Bunner et al., 1969, 1971) and by the Naval Research Laboratory (Henry et al.. 1968) soon upset the whole idea. They showed that the soft X-ray intensity decreased from high to low galactic latitudes much less than would be expected if the source were extragalactic and the decrease due to attenuation in galactic hydrogen. There was even a substantial intensity along the galactic equator where soft X rays from extragalactic sources must be almost totally extinguished by hundreds of optical depths of hydrogen. Kraushaar believed these results were strong evidence for a dominant galactic source of diffuse soft X rays. Yet a detailed examination of known mechanisms for interstellar X-ray production that might produce soft X rays showed they all had other consequences ruled out by observations (Williamson et al., 1974).

To resolve this conundrum Kraushaar planned a "shadowing" experiment to determine whether the observed soft X rays actually come from extragalactic sources beyond the Small Magellanic Cloud. The SMC is a nearby dwarf galaxy with enough interstellar hydrogen to block 250 eV X rays from more distant sources over a region of the sky extending more than 5 degrees in width. The plan was to use a recently developed attitude control system to point a rocketborne detector in a series of preprogrammed directions. The Wisconsin group constructed a new payload with soft X-ray detectors and honeycomb collimators that defined a narrow field of view that would be scanned across the SMC in search of a shadow. The experiment was launched from Woomera, Australia, on June 2, 1970. Its results placed an upper limit of 25 percent on the portion of cosmic X rays with energies in the range 120-284 eV that originates beyond the SMC (McCammon et al., 1971). In spite of this result the implications for a local source of soft X rays did not receive broad acceptance till 1974 when new theoretical and observational developments occurred.

Donald Cox, a theorist recruited to Wisconsin by Kraushaar, had been working on the evolution and X-ray emission of supernova remnants as they expand into and heat the surrounding interstellar gas. He and his students showed that the existence of a cold and uniform ISM, as it was generally thought to be, was inconsistent with the observed average rate of supernovae in the Galaxy and the heating they must cause. They concluded that a large fraction of the ISM is maintained by supernovae at temperatures near 1×10^6 K, where cooling rates are at a minimum (Cox and Smith, 1974). And observations with the new ultraviolet spectroscopy satellite, *Copernicus,* showed the ubiquitous presence of absorption lines of five times ionized oxygen (O VI) in the ultraviolet spectra of almost all the stars observed (Jenkins and Meloy, 1974). This ion is stable at temperatures near 3×10^5 K, which implies temperatures in the ISM that while not hot enough to produce the observed soft X rays, are far hotter than had been previously suspected. Shortly afterward, Lyman-alpha absorption lines observed with the same instrument showed the expected density of cool neutral hydrogen (~1 atom per cm^3) along the lines of sight to distant stars but not to any stars closer than about 300 light years. Thus it appeared that the Sun and its near neighbors are in a cavity with little or no neutral hydrogen, but filled with hot gas of which some is at a temperature near 1 million degrees and a density sufficient to produce the observed soft X rays by thermal excitation of the spectrum lines of elements heavier than helium. This radical new concept of the ISM spoiled the case for a hot intergalactic medium sufficient to reverse cosmological expansion. And it showed the need for an all-sky survey of soft X rays to understand the complexities of the ISM.

Already in 1970 Kraushaar had initiated a program that accomplished a complete all-sky survey in 10 sounding rocket flights over the next decade. The final results were presented in the form of maps of the diffuse X-ray background intensity covering the entire sky with ~7 degree spatial resolution in seven energy bands from 130 eV to 6.3 keV (McCammon et al., 1983; Burrows et al., 1984). The all-sky maps from the Wisconsin survey were the basis of most studies of the hot ISM for several years. They were supplemented by the soft X-ray surveys carried out with the *SAS*-3 and *HEAO*-1 satellites. Then in 1990 the German ROSAT orbiting observatory, equipped with a grazing-incidence X-ray telescope and imaging detector, surveyed the entire sky. During a year spent at the Max Planck Institute for Extraterrestrial Physics (MPE) as a Humboldt Foundation senior scientist, Kraushaar and MPE director Joaquim Trümper arranged for the Wisconsin group to collaborate in producing all-sky maps of the diffuse soft X-ray background from the ROSAT survey data (Snowden et al., 1995). The resulting maps had a hundred times greater statistical precision and angular resolution than the rocket maps and agreed with them in absolute intensities to within a few percent. The ROSAT maps became the standard surveys for energies from 150 eV to 2 KeV, while the old Wisconsin boron-filter map of X rays below 180 eV and scattered rocket observations with beryllium filters below 110 eV continued to place unique constraints on interpretations of the sources of diffuse soft X rays.

Kraushaar also led the development of three Wisconsin satellite X-ray experiments. The first, designated S-027, was a large set of conventional proportional counters with beryllium windows to be attached to the fourth stage of the Saturn V rocket. If it had been flown as originally scheduled, it would have been the first astronomical X-ray detector in orbit. Changes in the Apollo program delayed the launch by almost four years. Since this would put it after similar detectors had been in orbit on the Uhuru satellite, the instrument was completely rebuilt as S-150 with thin-window gas-flow counters and flown in 1973 on the Skylab-3 mission. Its data were used to place upper limits on the soft X-ray emission from normal stars, which showed that stars are not the source of a major part of the diffuse X-ray background (Vanderhill et al., 1975).

The second Wisconsin satellite experiment was a set of thin-window detectors on OSO-8, launched in 1975. These made precise maps over a small region of the sky, including the North Polar Spur, a large diffuse X-ray feature discovered on a sounding rocket flight a few years earlier. The OSO-8 data helped to show that this feature is part of a "superbubble" of very hot gas formed by multiple supernovae and stellar winds in an association of young stars.

The third experiment was the diffuse X-ray spectrometer, or DXS. Its purpose was to measure the atomic lines that were expected to dominate the spectrum of soft X rays from the hot interstellar medium and provide a wealth of detail about the elemental composition, temperature structure, and ionization state of the ISM. Kraushaar developed a curved Bragg crystal geometry optimized for diffuse sources, but it required a large-area Bragg reflector with 2d spacing greater than the wavelength of the softest X rays to be analyzed. No useful natural crystal like that exists, but Burton Henke at the University of Hawaii had developed a technique for stacking multiple monomolecular layers of lead stearate on glass microscope slides for soft X-ray spectrometry in his laboratory. So Kraushaar set up a small factory populated primarily by undergraduates in much the same style he had employed in developing the Explorer XI instrument to fabricate and test large quantities of this structure on thin Plexiglas substrates. The result was flexible panels coated with a 200-layer one-dimensional pseudocrystal with a 2d spacing of 101.5 angstroms that could be bent to conform to a particular curve. These were combined with a position-sensitive proportional counter and a mechanical collimator to limit the field of view. Bragg-reflected X rays of a given wavelength, incident from anywhere within the field of view, landed in a sufficiently narrow region of the position-sensitive counter to provide the required spectral resolution. The spectrometer provided a resolution of 2.2 angstroms or better over a wavelength range of 44-88 angstroms.

DXS was flown as an attached payload on the STS-54 mission of the space shuttle Endeavour in January 1993. At least 32 percent of the soft X-ray emission in the energy range 148-284 eV was found to be, as expected, line emission from partially ionized atoms of the hot ISM. However, efforts to fit the observed spectra, rich in detail, with models of the interstellar plasma were only partially successful due in part to a lack of adequate atomic emission data at the relevant temperatures. The results demonstrated the need for even better spectral resolution in future experiments, for better atomic data, and for more sophisticated models of the astrophysical sources (Sanders et al., 2001).

The program Kraushaar created at Wisconsin, particularly the rocket research, provided many opportunities for his students and young collaborators to take leadership roles in the preparation, performance, and publication of experiments, as reflected in the first authorship of many of the papers in his bibliography. Those experiences were the foundations for numerous careers in research and management of space science and technology.

DXS was Kraushaar's last major experiment. It fully bore out his early concern that orbital experiments would prove too lengthy to fit well into graduate education. It was originally proposed in 1972 for an Explorer mission. After numerous stops and starts and cliff-hanging administrative decisions at NASA, it finally flew 21 years later. By that time Kraushaar had retired from teaching (in 1985) though he continued active in research until he moved to Maine in 1998 with his second wife, the former Elizabeth DeMoss Rodgers, whom he had married in 1982.

RECOLLECTIONS

Aside from physics, Kraushaar loved nature and the out-of-doors. While at MIT he designed a cabin on the shore of a pond in Maine where he spent most summer vacations with his family. After moving to Wisconsin, he built a shelter in the woods of the western part of the state. These construction projects brought him great satisfaction, as well as good access to his favorite pastime of walking in the woods. He was an avid mushroom hunter but modest about his knowledge. "I only collect the few I know," was his usual comment, though on a walk you soon realized that he could answer any question you might ask about any odd little fungus you came across. His daughter wrote, "My father loved the woods, the quiet, and the simplicity of our life in Maine in the summers. I considered the person I saw during our time in Maine at the cabin, to be the real Bill Kraushaar. He was creative and fun and playful. He would spend his time there walking in the woods, mushroom hunting, sailing, canoeing, reading, or at his workbench creating some little gadget that he thought up."

Kraushaar was known as much for how he did science as for what he did. Alan Bunner recalled, "I was astonished when, as a brand-new post-doc, young and green, he said, "Alan, there's an important meeting at NASA Headquarters concerning a future space observatory. I don't want to go. Why don't you go in my place?" I found myself surrounded by all the senior founders of X-ray astronomy, talking with Nancy Roman about LXO, later to become Chandra."

Good training it was indeed for Bunner, who much later became head of High Energy Astrophysics at NASA and oversaw much of the Chandra development program. He also noted,

> Bill was extraordinarily polite, patient, and forgiving. I recall once when I made a totally stupid remark (about physics in 2 dimensions, I think), he puffed on his pipe, looked me in the eye, and quietly responded, "Are you sure?" It was enough.
>
> He trusted his students in a way that is uncommon. I don't recall his ever going on a sounding rocket launch. He trusted his students and post-docs to get it right, and learn by doing. [One of these students, an author of this memoir, never appreciated how truly difficult this was until he had students of his own.]
>
> Bill had little enthusiasm for the mountainous paperwork of the NASA bureaucracy. We got an experiment approved for the Post-Apollo program. It was the manned space program, and Marshall Space Flight Center insisted on reams of detailed procedures, books of stuff that no one would read. It was a daunting task, so Bill said, "Let's just tell Marshall that they have to do it all for us." We told them, and it worked.

Kenneth Greisen best captured what was special about Kraushaar as a scientist. In a letter recommending Bill for a named professorship at Wisconsin he wrote,

> It is probably unnecessary for me to recite his achievements. But I want especially to point out the unassuming, non-aggressive, charitable, diplomatic and self-effacing manner with which these achievements were made. Others do such things by completely self-centered, driving ambition, but not Bill: his concern is always to give credit to others, not to claim it for himself. I have in my memory a small treasure house containing remembrances of people whom I regard as fine role models of scientists who are good in every way. Bill Kraushaar is among the small number of occupants.

Kraushaar's broad view of science and unselfish outlook made his opinion highly sought after. He served on innumerable national advisory committees. He was a member of the National Academy of Sciences (elected in 1973), the American Academy of Arts and Sciences (in 1961), and a fellow of the American Physical Society. In addition to the Fulbright fellowship in Japan, he was a Guggenheim fellow at Harvard and Caltech (1963) and at Leiden (1973), and was a senior scientist of the Humboldt Foundation at the Max Planck Institute for Extraterrestrial Physics (1983). He lives on in the memories of all who knew him, and especially those who worked with him, as a wonderful example of what we all should strive to be.

CHARACTERISTICALLY, BILL NEVER WROTE ANYTHING ABOUT HIMSELF. For details we have been entirely dependent on the personal recollections and memories of his colleagues, friends, and family. We are grateful for each of these contributions, and would like in particular to acknowledge Jack Kraushaar, Sigenori Miyamoto, James Earl, Donald Cox, Thomas Cline, Frank Scherb, Gordon Garmire, Alan Bunner, Wilton Sanders, Yasuo Tanaka, and Sunna Kraushaar.

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