1. It all began with a rocket …

My story, and for me, the story of multiwavelength astronomy, begins with the rocket. Without it, space science would not exist, and my life would have turned out very differently.

The American physicist, Robert Hutchings Goddard, was an early pioneer of rocket technology, but the German engineer Wernher von Braun mastered it. Developed by von Braun in the 1930s, the V-2 rocket was used during World War II to deliver one-ton warheads at supersonic speed from Germany to southern England. At War's end, parts of captured V-2s were brought to the U.S. and assembled by the Army at White Sands, New Mexico, to be used for research and experimentation by government agencies and universities. I was a young scientist at the U. S. Naval Research Laboratory (NRL) when my group began its observations of the Sun using Geiger counters carried aloft by the rebuilt V-2s. With them we were the first to discover X-rays from the Sun.

Growing up I was surrounded by art, music, and literature. When I entered college there was no suggestion that I would end up a scientist. I think my orientation towards the arts gave me a subliminal fascination with beautiful devices. I'd never thought about space travel, and I didn't know enough about physics to realize what kind of excitement lay ahead. The rocket changed the course of my life.

2. Growing up

I was born in New York in 1916, the middle child. I can't remember much about school in those early years, except that I couldn't see over the seat in front of me. I was that small. I liked math and was always interested in reading, but I was never impressed with science fiction, like Buck Rogers.

I had some talent as an artist and my family recognized it. In our financial circumstances, there was never any question about going to a private school. The routine was to live at home and go to free public college. For those of us who lived in Brooklyn, it was Brooklyn College. I started out as an art major. I also took a lot of math because it came easily to me. By the time I had finished my sophomore year, I had decided that I really didn't want to continue as an art major. For one thing, I was the only boy in classes that were otherwise all female.

I took a physics course and found I liked it very much. In my last two years of college I took almost nothing but physics. By the time I graduated I was a physics major. There were, all told, about ten physics majors in what must have been a population of 10 to 20 thousand students at Brooklyn College. I had no idea of going on to graduate school. Physicists weren't in demand and no one really understood what they did. Later, when friends would ask my mother "What does your son do?" she'd say, "He's a physicist." "What does a physicist do?," they'd ask. Her reply was, "Oh, he does what Einstein does."

3. Graduate School

After I graduated I hunted for a job in commercial art, without success. I applied to graduate school at Johns Hopkins and also at Cal Tech, because my buddy was planning to go there. Well, my family decided where I should go. In 1936 it cost about $2.50 to go to Baltimore from New York, but it cost $40 to go to California. My mother felt if I ever got that far away, I'd never come back, so she insisted I go to Hopkins.

I vividly remember my first day in the physics department at Hopkins. The secretary took me down to see Professor James Franck. I hardly knew who he was at that time. He was a Nobel Prize winner and a truly great man. And he had a very fatherly look about him, sort of a portly, handsome man. He smoked a big cigar, and ashes kept falling on his vest, but he was totally indifferent to it. He was very relaxed, and talked to me for about two hours. He tried to understand what my aptitudes might be, and to prescribe courses, and sort of generally indicate the direction I might take. I appreciated only later on what it meant to have two hours of James Franck's time and that kind of discussion as a new student.

I decided to do my thesis work with Franck and he was willing to take me on. Then, just when I was getting organized to start my research, he moved to the University of Chicago, where they set up the Franck Institute. But I went ahead with my research, developing a Geiger counter that improved the sensitivity of an ionization chamber used to detect X-ray particles. Within a month I had enough data to write my thesis. Then I wrote several other papers studying X-ray interactions with materials using this instrument.

4. Wartime Physics

After graduation it was tough getting work as a physicist, but I finally got a job at the Naval Research Laboratory working in the Metallurgy Department, doing all sorts of applications of X-rays and gamma rays. Then, during the war, I was working on developing detectors for radiation. Immediately after the bombing of Japan, we wanted to send in survey teams to map out the distribution of radioactivity from the epicenter of the bomb. I had made a number of portable exposure meters and actually published descriptions of them, but surprisingly, there didn’t seem to be any instruments of this type in the Atomic Energy Project. They had all sorts of instruments for measuring radioactivity, but no portable battery-operated devices. We put together some radiation devices, calibrated them, and equipped their team to make the survey of Hiroshima and Nagasaki. From there on the Navy had a great concern for radiation problems connected with atomic warfare: how to decontaminate ships and other facilities that had been exposed to atomic bomb attack, and generally how to monitor areas for contamination. We worked with the Navy for many years developing a whole catalogue of devices for detecting different kinds of radiation.

I didn't know that we had developed the bomb when I learned about the bombing of Hiroshima. As the story came out, the feeling was one of very great horror. There was concern on the part of all scientists, I think almost immediately, that we had developed something terrible.

5. Early Rocket Experiments

When I was 26 years old, I was offered a position leading the newly formed Optics Division at NRL. The head of the division was Edward O. Hulburt. Very early on he thought there must be something like X-rays from the Sun, although he didn't have any idea how they could be produced.

After the V-2 came along people at NRL began doing rocket experiments, at Hulburt's urging. My first rocket experiment in 1949 was designed to observe solar X-ray and ultraviolet radiation. I had prepared a collection of detectors that would isolate, what seemed to me, the most interesting regions of the spectrum: a detector that would concentrate on X-rays, and in the right wavelength range, to explain why the ionosphere is produced at 100 kilometers, and a detector that would isolate the Lyman alpha line of hydrogen, which could be the strongest ultraviolet line in the Sun. And there was another detector that would concentrate on longer wavelengths that are absorbed by molecular oxygen in the upper atmosphere. At the time fewer than half the launch attempts were successful, but beginner's luck was with me. My rocket performed and I was able to obtain results up to an altitude of 150 km (MILES). In a very simple experiment, we answered several of the classical questions about solar radiation and the upper atmosphere. The discovery of solar X rays is widely attributed to me based on this early rocket experiment.

One of the problems with the V-2 was that it was so large that everybody and his cousin wanted to put an experiment on it, and having all of those experiments in one payload was hard to manage. Jim van Allen had the idea of using small rockets, called Aerobees, for carrying just one experiment at a time. The Aerobee was small and cheap, but it didn't have enough propulsion to bring us to the top of the ionosphere, so we modified it by extending the fuel section, which did the trick. We were able to make the first attempts at space-based astronomy by putting small 4- to 6-inch mirror telescopes in Aerobees, and observing the fluxes of stars in the ultraviolet. We were in that mode, working with Aerobees, until the Sputnik era came along.

6. The Sputnik Era

The Sputnik launch in 1957 was a shocker. We had been meeting all week with the Russians at the National Academy, in which we were describing our respective rocket programs, Sputnik and Vanguard. During the discussions we had the sense that we were ready to launch and they were not, and yet they were giving us signals that we just didn't appreciate. By the end of the week of that meeting, the news came that the Russians had succeeded in launching Sputnik, and it really took us completely by surprise.

The following year I went to Moscow for some meetings. The Russians had an exhibit at their Industrial Fair in which they showed Sputnik I and Sputnik 2 and the instrumentation that went into them. It surprised all of us who were there to actually see this because back home we were just guessing: what kind of technology did they have? and how had they put it all together? And there it was, spread out right before our eyes. One of the components in Sputnik 2 was a Geiger counter.

Before I left Russia I visited a science supply store, and in the store window was the counter that I had seen in Sputnik 2! I was there with John Simpson of the University of Chicago. We each bought a counter at something like a ruble a piece. I wondered, Will they let us take these out of the country? So at the airport I stuck the counters in my coat pocket like two cigars, and I just walked through. It worked! The Russians were very relaxed at that time, and they didn't frisk us. After I got back to the U.S., one of our intelligence people came in to talk to me. I had the counter on the table, and I casually mentioned that this was the Sputnik counter. He was shocked! Then he asked to borrow the counter, with promises to return it undamaged and so on. Months later the counter came back to us, now as a classified secret.

7. Counters vs. Mirrors

Immediately after Sputnik everything loosened up. NASA was established and interest in doing space science accelerated. In the early 1960s, different groups were moving along independent paths toward what would eventually lead to NASA's *High Energy Astronomical Observatory* (*HEAO*) program.

Using rocket-borne detectors, my group at the Naval Research Laboratory had been studying the X-ray emission from the Sun for over a decade, but we were unable to detect X-rays from sources outside the solar system. What was needed, I felt, were larger detectors with better efficiency and larger area. Of course, no one knew for sure just how efficient the detectors would have to be, since the properties of the X-ray sky beyond the solar system were a complete mystery. If all the stars were about the same strength as the Sun, then detectors thousands of times more efficient would be needed. This would mean detectors with thousands of times more area than those currently in use or an X-ray telescope - which didn't then exist - that could focus many X-ray photons into a small area.

The idea of a focusing X-ray telescope as the solution to this problem captured the imagination of two physicists in Cambridge, Massachusetts, Bruno Rossi at the Massachusetts institute of Technology (MIT) and Riccardo Giacconi at American Science and Engineering (AS&E). In 1960, together they published a landmark paper advocating the use of grazing incidence reflectors to study cosmic X-rays, and predicted the Crab Nebula as a potential source.

At the time, I think everyone knew you could build an X-ray mirror, but the technology was still rather far off.

8. **Friendly Competition**

On June 18, 1962, the AS&E team launched an Aerobee rocket from White Sands, New Mexico. Its payload was 3 Geiger counters. The flight, which only lasted a few minutes, was intended to detect X-rays coming from the Moon. Instead, the Geiger counters detected a dim, uniform glow across the sky and one brilliant source in the constellation Scorpius. The X-ray detectors also found a possible second X-ray source in the general direction of Cygnus and Cassiopeia. The team at AS&E published their results at the end of the year. The X-ray source was a binary star system designated Scorpius X-1. Sco X-1 was the first cosmic X-ray source discovered, and, aside from the Sun, it is the strongest source of X-rays in the sky. Then in the spring of 1963, we flew a new NRL-developed X-ray detector system that confirmed these results and more. Our detector showed clearly Sco X-1 as the strong source of emission and we gave its position more accurately (about half a degree) than the AS&E experiment. Another source we found was the Crab Nebula.

We continued our experiments as part of an ongoing effort to map these sources, using rockets carrying Geiger counters to measure X-ray emission. These instruments swept across the sky as the rockets rotated, producing a map of closely spaced scans. As a result of these surveys, eight new sources of cosmic X-rays were discovered, including Cygnus X-1, which we were able to confirm as the possible second source in the AS&E rocket flight. By 1965 we had a catalogue of 30 sources, but we had reached the point where it was obvious that you couldn't fire enough rockets to give you an adequate enlargement of the X-ray catalogue. It would take too long to do it that way. Although rockets paved the way for X-ray astronomy, a satellite's ability to maintain a position in space for long periods of time would allow the counters to measure and record more data about X-ray sources.

9. From Rockets to Satellites to Observatories

So who was prepared to go into space science? In the early days, there were very few astronomers involved in rocket and satellite research. I have a physics background, yet I was doing astronomy. (I never had a course in astronomy!) And at the time, astronomers were still being trained along classical lines and very few of them could see the possibilities of space research, with a few exceptions, like Lyman Spitzer, who pioneered the idea of a space telescope. But things were changing quickly. For example, the original emphasis of NASA had changed somewhat from its earlier purpose of proving technological superiority over the Russians. When in 1961 President Kennedy said "We will go to the moon," NASA essentially was given a new goal. A lot of scientists thought that this would be the end of space science, but I felt it caught the imagination of the public, and ultimately that manned missions would open new frontiers to astronomy.

Of course space science continued even as NASA began the *Apollo* Program in 1963. Throughout the 1960s NASA's satellite programs, the *Orbiting Solar Observatories* (OSO) and *Orbiting Astronomical Observatories* (OAO), carried out experiments in the ultraviolet and X-ray energies that heightened awareness within the astronomical community of the significance of space-based observations. There were also people at Marshall Space Flight Center, in particular Ernst Stuhlinger, who wanted to try to develop a scientific payload for a post-*Apollo* mission. His idea was that we could do manned experiments using some of the leftover *Apollo* hardware. At a Space Science Board meeting we discussed what might be done. There, too, Giacconi emphasized the telescope, but I thought we could carry 100 square feet of X-ray detector on the *Apollo* hardware. This concept of using large area detectors would ultimately lead to the *High Energy Astrophysics Observatories* (*HEAO*) program.

10. The Space Shuttle and Space Telescope

The success of the *Apollo* program and results from the *OSO* and *OAO* satellite missions boosted our confidence in pursuing space science on a grand scale. Soon after taking office in January 1969, President Richard M. Nixon established the Space Task Group, composed of NASA engineers, to answer the question, "What's next for NASA?" Their report, issued after the successful flight of *Apollo 11*, recommended a national space strategy that would include building a space transportation system to carry passengers, supplies, rocket fuel, other spacecraft, and equipment to and from orbit on a routine aircraft-like basis. I was appointed to the President's Science Advisory Committee and chaired a panel in which we came around to the present space shuttle concept. The original idea of a fully recoverable system launched from the ground was going to cost over 13 billion dollars. President Nixon said he wanted us to come back with something closer to six billion, so a shuttle in which you dispose of the fuel tanks and bring back only the orbiter was the concept that we reached.

About the same time, a group of 90 scientists gathered for more than two weeks at Woods Hole, Massachusetts, to deliberate on priorities and recommend levels of effort and support to be allocated to the various NASA programs. I chaired the executive committee that produced the *Priorities for Space Research 1971-1980* report in 1970, in which we recommended NASA initiate a new program to orbit a telescope of at least 1.5-m aperture. We also gave very high priority to begin the *HEAO* program to study X-rays, gamma rays, and cosmic rays.

The timing was right. Research in high energy astronomy was ready for major advances that could be expected from the large-volume payloads *HEAO* could carry. Two missions were deemed essential, a scanning mission, and a pointed mission.

11. The High Energy Astronomy Observatory Program (HEAO)

The first mission of the *HEAO* program would have a very large array of X-ray detectors, and the second one would have the *Einstein* telescope. The Naval Research Laboratory was selected to develop one of the four instrument packages to be flown on the *HEAO-I* satellite, which was launched in August 1977. Our package, the Large Area X-Ray Survey Array, consisting of seven modules of large-area proportional counters, was the largest space instrument ever to be flown on any satellite at the time. An improvement over the Geiger counter, proportional counters could detect the presence of an X-ray and measure its wavelength. *HEAO-1* scanned the entire sky for high-energy sources, which included radio pulsars, binary pulsars, black holes, quasars, and extragalactic X-ray sources, resulting in a new map of nearly 1,000 discrete X-ray sources. Given this, you would never know that we had problems with the *HEAO* payload! After launch we lost the detectors, one by one. We ended up with two that were working well, two that were working partially well, and three that were totally defunct. We wished we had had more time prior to launch so that we could have done better testing and come out with better performance. On the other hand, what worked produced very beautiful results.

A year later, *HEAO-2*, renamed *Einstein* after launch, carried the first fully imaging X-ray telescope into space, built by Riccardo Giacconi and his team. It returned detailed quasar images and discovered that Jupiter and Earth emit X-rays. *Einstein* made over 5,000 pointed observations and discovered several thousand serendipitous sources that fell within the field of view of its imaging instruments. It opened up X-ray observation to all classes of celestial objects, including auroras on planets, supernovas, galaxies, quasars, and sources of X-ray background radiation.

12. The Amazing Universe

The *HEAO* program was only the beginning. The vision for space research thus far laid the foundation for building a space transportation system and refining the telescope technologies that would result in NASA's *Great Observatories Program*. NASA launched the Hubble Space Telescope in 1990, followed by the Compton Gamma Ray Observatory (1991), the Chandra X-Ray Observatory (1999), and the Spitzer Space Telescope (2003), using the Space Shuttle to carry these observatories into low-Earth orbit where they would open a vast, new window on our amazing Universe.

From time to time I have been asked my opinion on how space research benefits society. It's hard to put a price tag on this. As time goes on, the science we get in return for every dollar invested rises, in spite of the fact that the costs go up, too, because the information retrieval goes up orders of magnitude with each new mission. If you work on the frontiers of science, you're bound to contribute to society in very beneficial ways, because that's where the new applications and new technologies will come from. Basic research leads the technology, and if we don't have creative science, we won't have productive technology–or innovation (a good word we all use now). And you don't get creative science unless you have a flow of fresh young minds into the field.

Science is a field that needs young minds that see things differently and are open to adventure. When you are young, you have the stamina to do rigorous research, to work on a problem that intrigues you for 14 or 16 hours a day! And it’s immensely rewarding, because science allows you to try something new and provides a great sense of adventure that lasts a lifetime. When I was young I had a general philosophy of looking into any region of the spectrum that had not been explored, and this was part of the adventure for me. I had just the gut feeling that there were surprises everywhere one could look, and it was a mistake to ignore any part of the spectrum. The ultimate excitement of X-ray astronomy in my era was that it really was a new astronomy. We saw things very differently and what we saw related to very exotic processes, like supernova collapse, formation of neutron stars, and black holes. I can't think of more intriguing problems in astronomy. Can you?