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Considerations on X-ray astronomy

A start in X-ray astronomy

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Abstract. Remarks on the history of x-ray astronomy. The successes of x-ray astronomy were not a fluke, but the result of the bounty of Nature, the aspirations of many people, a fairly rigorous and methodical research effort, and the development of new technology and new operational approaches. In the last 50 years we have made great steps in our physical understanding of what the x-rays have shown us. We have made a progress of 10 billions in sensitivity. We have developed the know-how and the methods to build even more powerful observatories that will carry us into the next 50 years of discovery and understanding.

Key words. X-ray astronomy

1. Introduction

The last fifty years have seen a rapid development of observational x-ray astronomy from the discovery of the first extra solar x-ray source Sco X-1, to the detection of celestial objects 10 billion times fainter. This remarkable improvement has allowed detection and study of the x-ray emission from all known celestial objects and has opened to our view the high energy universe, from the formation of young stars to the study of the most distant clusters of galaxies and AGNs. The story of the early beginning of x-ray astronomy has been very well described by Richard F. Hirsh in his PhD Thesis (Hirsh 1979) and summarized in his book "Glimpsing an Invisible Universe" (Hirsh 1985). A more personal view was given in "The X-ray Universe" by Tucker & Giacconi (1985) and in "Secrets of the Hoary Deep" by Giacconi (2008). I thought that the most useful contribution I could give to this meeting, designed to celebrate fifty years of accomplishments and to look to fifty years in the future, would be to attempt to clarify some confusion about the past and to express my hopes for the future of the discipline.

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2. Opportunities in x-ray astronomy

Given that x-rays can not penetrate the Earth's atmosphere, one can set the start of interest in exploring the sky in x-rays to the development of the V-2 rockets during War World II and more clearly to the launch of Sputnik on October 4,1957.

The Naval Research Laboratory group led by Herbert Friedman made use in 1948 of V-2 rockets, captured by US troops in Germany, to investigate the radiation producing the ionization of the Earth's atmosphere with the clear conclusion that it was due to solar coronal x-rays. The NRL group was the undisputed leader in solar x-ray astronomy during the 1948-1959 period. Although the group attempted to observe emission from other stars, they were unsuccessful due to the very low flux from extra solar sources and the design of their experiments.

The launch in 1957 of "The New Red Moon" by the Soviet Union had very significant repercussions in the US due to what was considered to be not only a major assertion of Soviet technological prowess, but also to have defense implications. In response to this challenge President Eisenhower established the National Aeronautics and Space Administration to integrate civilian efforts in 1958. In the same year the National Academy of Sciences created the Space Science Board with the task of examining the scientific opportunities presented by space investigations. The SSB proceeded as usual by establishing several committees in Physics and Astronomy.

As early as October, 1958, John A Simpson, Chair of the Committee of "Physics of fields and particles in space" suggested in an interim report mapping the sky in gamma and x-rays (Simpson 1958).

Lawrence H. Aller (Optical and Radio Astronomy Committee) pointed out in 1959 that x-rays could reach the Earth from galactic distances and that many stars and nebulae would be detectable in wavelengths shorter than 20 Angstrom, provided one developed the necessary instruments (Aller 1959).

Leo Goldberg in the report of the same committee (Oct. 24, 1959) emphasized, "Instrumentation for x-ray optics is in a very rudimentary state and for image forming optics non existent".

Bruno Rossi participated in these discussions and was appointed Chairman of the Ad Hoc Committee of Space Projects on Sept. 30, 1959.

2.1. Learning

In September 1959, I had joined American Science & Engineering, a small private company (27 people) created by its President, Martin Annis, to carry out scientific research for the US Government in the fields of Defense, Education and Medicine. Bruno Rossi was the Chairman of the Board.

The company hired me at the end of my Fulbright Fellowship at Indiana and Princeton Universities to initiate space research activities. I met Bruno Rossi for the first time in the Fall of 1959, at a party in his house. He suggested that among other possibilities I could consider x-ray astronomy as a potential subject of study. In typical Italian fashion he did not relate to me the discussions, which had taken place at SSB, presumably with the view that the young man could figure it out by himself.

Up to then I had been working in cosmic ray and particle physics at the University of Milano with Giuseppe Occhialini, at the Indiana University with Robert W. Thompson and at the University of Princeton in the cosmic ray group of George Reynolds. I had therefore to start anew in learning about x-ray physics and x-ray astronomy. I studied the Compton and Allison 1935 fundamental book "X-rays in theory and experiment" and brought myself up to date by reading the relevant parts of Springer Verlags "Encyclopedia of Physics" edited by Flugge. I found a Russian publication of 1958 "The Russian Literature of Satellites", which in an article by S.L. Mandel'shtam and A.I.Efremov (Mandel'shtam & Efremov 1958) described in some detail H. Friedman's solar work in the period 1948-1958 and some theoretical studies by Elwert and De Jager. They also mentioned the upper limit for extra solar sources of 2×10^{-8} erg cm^{-2}sec^{-1} for 6 keV photons reported by NRL.

2.2. Thinking

The first obvious result from this learning was the very low fluxes of X-rays to be expected from non-solar sources. While solar coronal emission below 20 Angstrom resulted in 10^6 cts cm^{-2} sec^{-1}, the emission from Sirius at a distance of 8.6 light years would produce at most only 0.25 cts cm^{-2} sec^{-1} even if we adopted the extreme assumption that it emitted as much in x-rays as in visible light. Coming from a discipline (cosmic rays) that

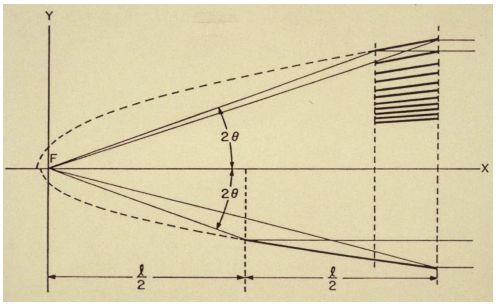

Fig. 1. A telescope for x-ray astronomy (Giacconi & Rossi 1960), shows a single reflection design using nested parabolic mirrors at grazing incidence to fill the aperture.

could no longer contribute significantly to particle physics research due to the low particle fluxes, I was quite concerned that x-ray astronomy would be severely constrained by poor statistics.

Two years of observations at the Testa Grigia Observatory (elevation 3500 meters) had been necessary to collect the 80 proton interactions on which to base my thesis research on the Fermi fireball model. I had dreamed then of a magic magnetic funnel that could concentrate cosmic rays on my cloud chamber. Could I realize such a collector for x-rays? The answer was yes! By using a parabolic grazing incidence mirror I could focus incoming x-rays from a large collecting area onto a small detector thereby increasing the sensitivity of the instrument by several orders of magnitude. Such a telescope did not exist in x-ray astronomy, but I felt that there were no physics obstacles but only technical ones in its development. Thus I was certain that after developing such a telescope x-ray astronomy could be done.

As soon as I hit on this idea Martin Annis called Bruno Rossi, who expressed great interest, and immediately came up with an improvement, namely the idea of nested mirrors (Fig. 1). We submitted a paper, "A telescope for soft x-ray astronomy" in December 1959 (Giacconi & Rossi 1960). In cooperation with George W. Clark and Bruno Rossi of MIT by January 15 1960 I wrote a technical note "Brief Review of Experimental and Theoretical Progress in X-ray Astronomy" (Giacconi, Clark & Rossi 1960). We considered several mechanisms of x-ray production including black body, optically thin thermal bremstrahlung, synchrotron emission and inverse Compton scattering of relativistic electrons on optical or infrared photons. We considered several potential sources as shown in Table 1, and we came to the conclusion that fluxes from extra solar sources would indeed be most likely of order of 10^{-6} the flux from the solar corona. Following Aller's suggestion that interstellar space was transparent (as far as the galactic center) to x-rays of energy greater than 1 keV (Aller 1959) and that grazing incidence total reflection could efficiently focus photons of less than 10 keV, we noted the very important window between 1 and 10 keV for X-ray Astronomy (Fig. 2).

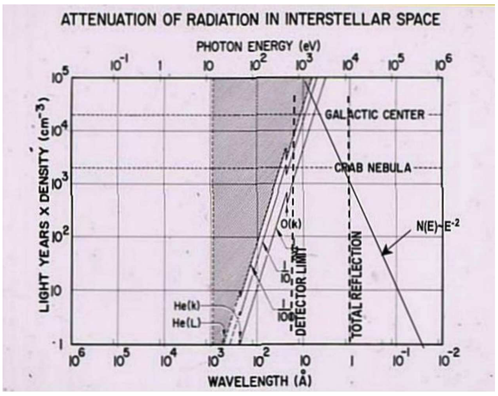

Fig. 2. Attenuation of radiation in space due to the interstellar medium. Vertical lines indicate the short wavelength cutoff for grazing incidence optics and the long wavelength cutoff for seeing the galactic center.

I also examined critically the experiments carried out by the NRL group to detect extra solar sources. While their approach was sensible for ionospheric and solar x-ray studies, it seemed to us unsuitable to study the faint fluxes expected from other stars.

I thought there were three principal problems with the NRL surveys: I) Exploring the sky for unknown sources with a narrow field of view (3 degrees) would require a large number of flights (~ 100) to scan the entire sky, thus

Table 1. Possible sources of x-rays and their estimated fluxes, taken from Giacconi, Clark & Rossi (1960).

Source	Maximum Wavelength	Mechanism for Emission	Estimated Flux
Sun	< 20Å	Coronal Emission	$\sim 10^6$ cm^{-2}sec^{-1}
Sun @ 8 Light Years	< 20Å	Coronal Emission	2.5×10^{-4} cm^{-2}sec^{-1}
Sirius if $L_x \sim L_{opt}$	< 20Å	? No convective zone	0.25 cm^{-2}sec^{-1}
Flare Stars	< 20Å	Sunlike Flare?	?
Peculiar Stars	< 20Å	$B \sim 10^4$ Gauss Large B Particle acceleration	?
Crab Nebular	< 25Å	Synchrotron $E_e \sim 10^{13}$ eV in $B = 10^{-4}$ Gauss Lifetimes?	?
Moon	< 20Å	Impact from solar wind electrons $\Phi_e = 0 - 10^{13}$ cm^{-2}sec^{-1}	$0 - 1.6 \times 10^3$ cm^{-2}sec^{-1}
Sco X-1 (1962)	2 – 8Å	?	28 ± 1.2 cm^{-2}sec^{-1}

providing a 1% chance to sweep through any particular source. II) No attention was given to the background produced by high-energy cosmic ray particles traversing the counter. In the Geiger counters used, the cross section sensitive to cosmic rays exceeded the area of the window sensitive to x-rays by a factor greater than 20 (and possibly as large as 200). Since the cosmic ray flux is about 1ct cm^{-2} arcsec^{-1} and the expected x-ray photon flux for extra solar sources is only 1 cm^{-2} arcsec^{-1}, this implies a signal to noise ratio of less than 1/20. III) Clearly the cosmic ray rate had to be much reduced either by making the cross section of the counter sensitive to cosmic rays not much larger than the area of the x-ray window and/or by using an anticoincidence system to accept x-rays and reject cosmic rays. This required the ability to count single photons, rather than measuring the average flux. The use of anticoincidence required the transmission of digital information on an analog telemetry signal. The net result was that the cosmic ray background was reduced to a negligible fraction of the isotropic extragalactic x-ray background which could therefore first measured in the June 1962 flight.

2.3. Planning

Planning for a new space program unfortunately included not only scientific considerations but also the need to find financial support for the design and development of the necessary instruments and for the means of placing them above the Earth's atmosphere.

We were able to interest John Lindsay a solar astronomer at Goddard Space Flight Center to support the "Design, Construction and Testing of a prototype X-Ray Telescope" (NAS-5-660) starting in October 1960. This program ultimately culminated in the flight of a 30 cm diameter x-ray telescope as part of the ATM instruments flown on the first US Space Laboratory SKYLAB in 1973.

Our proposal A measurement of soft x-rays from a rocket platform above 150 km (AS&E P -26, 17 February 1960) was not accepted by NASA Headquarters, with the sarcastic question by Nancy Roman of why should NASA support a search for x-ray stars which were not known to exist. Actually because of J. E. Kuperion of Goddard Space Flight Center advocacy, NASA supported two groups: Philip Fisher at Lockheed from Nov. 1961 and Malcolm P. Savedoff at the University of Rochester from June 1959 and partly supported the NRL effort.

We turned then to the Air Force Cambridge Research Laboratory and we were able to interest John W. Salisbury (Chief of the Lunar and Planetary exploration Branch) in the possibility of detecting fluorescent x-rays from the Moon, which after all was the only extra solar source we could count on.

Our scientific planning consisted therefore in following two paths: I) the development of x-ray telescopes to be used initially for solar astronomy and later, when sufficiently advanced, for stellar astronomy. II) the development of instrumentation more sophisticated than hitherto used, in the hope that even without the new x-ray optics we could observe the brightest celestial sources. We considered the limit to the flux of as reported in 1959 by the NRL (2×10^{-8} erg cm^{-2} sec^{-1}) to be only a tentative number, given the very high noise in their measurements and the tiny portion of the sky explored. In any case we concluded that an improvement by a factor of 50-100 in sensitivity, which we deemed feasible, could lead to new results.

2.4. Do

Beginning in October 1960 we began to develop the x-ray grazing incidence imaging telescopes using the optical design described by Wolter for microscopes (Wolter, H. 1952; Giacconi & Rossi 1960) and using a variety of techniques (Fig. 3), which resulted in the development of optical systems with greater and greater collecting area and angular resolution. We tested these telescopes in a number of rocket flights (Fig. 4) for solar research and in 1973 we were able to study from Skylab the x-ray emission by the solar corona during several solar rotations with an angular resolution over the entire sun of better than 5 arcsec.

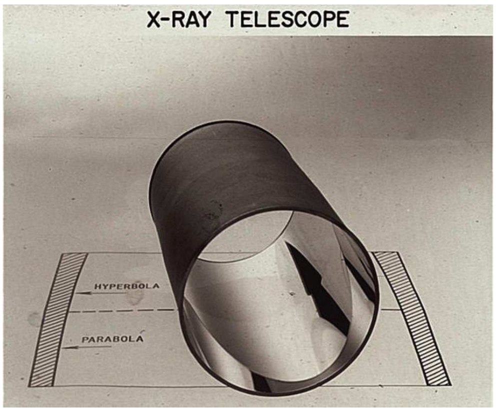

Fig. 3. Wolter-I x-ray telescope made as a Ni replica from a polished mandrel in 1963.

As to the search for extra solar sources, we developed Geiger counter detectors with $10 cm^2$ window area each. The detectors were housed in a scintillator well, which provided the anticoincidence signals for cosmic ray rejection. Three such detector systems were installed in each rocket flight and the field of view was made as large as 120 degrees to increase our chance of success (Fig. 5). After rocket failures in 1960 and in 1961, the first successful flight in 1962 led to the discovery of Sco X-1 (Giacconi et al. 1962).

The results are reproduced in (Fig. 6) and they show the detection of Sco X-1 and of the isotropic extragalactic x-ray background measured in two bands of the x-ray spectrum. Had we flown at a different time of the year we would have detected the Crab Nebula emission as we did in fact observe in the October 1962 flight.

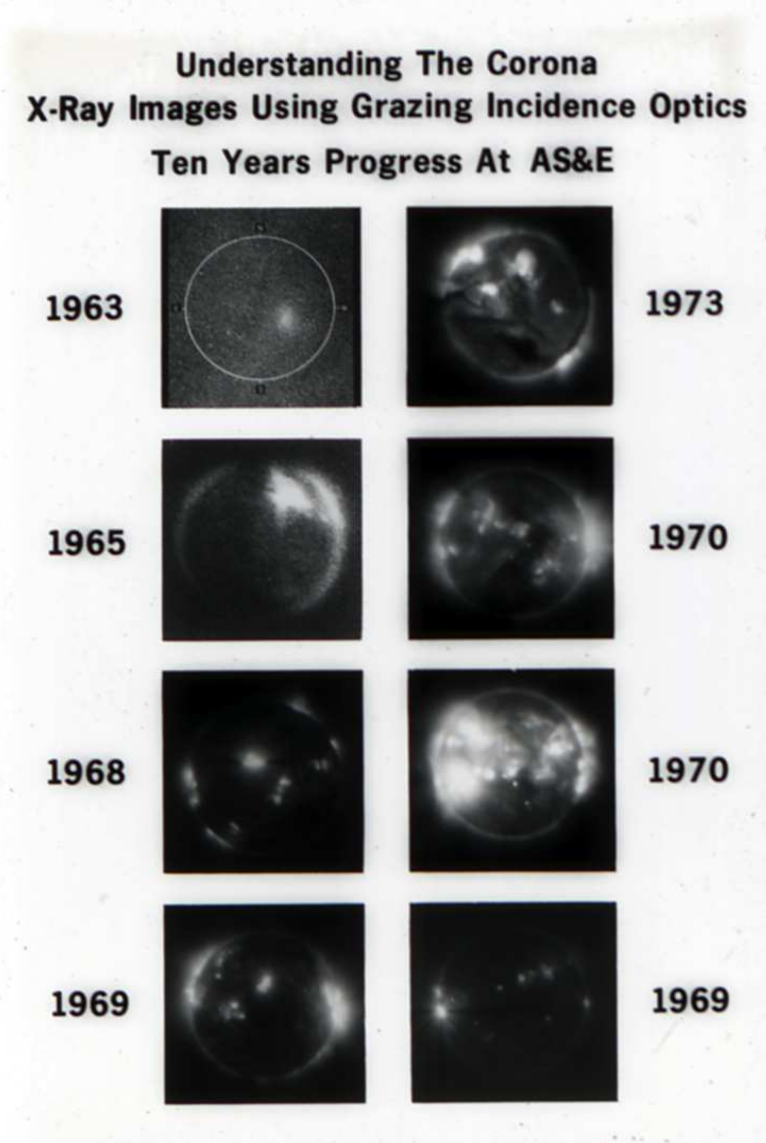

Fig. 4. Progress in solar x-ray observations from 1963 to 1973 and the Apollo Telescope Mount (ATM) telescope with better than 5 arcsec resolution.

I hope to have made clear in my discussion that impetus for this research was not due to a single person intuition, but to a broad consensus of interests among physicists and astronomers. It also should be clear that the discovery of Sco X-1 was not a serendipitous discovery as sometime described, but the successful result of a carefully planned and executed experiment.

3. The Post Sco X-1 Era

In the preceding sections I have used as subtitles "Learn-think-plan and do", a brief re-

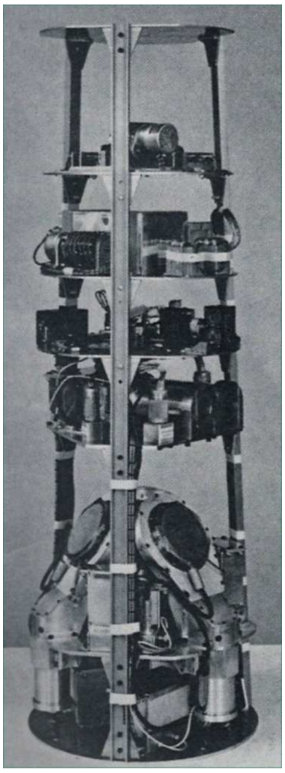

Fig. 5. Rocket payload from 1962 that discovered the non-solar x-ray source Sco X-1, and the cosmic x-ray background.

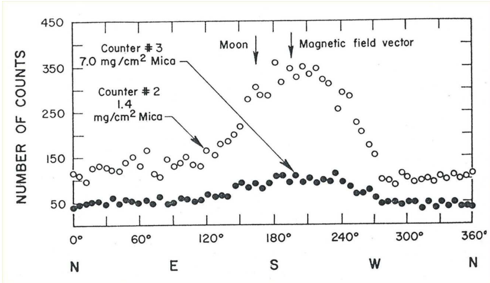

Fig. 6. The results from the June 1962 rocket flight showing the detection of Sco X-1 as well as the isotropic x-ray background.

minder of our methodology. This is because I believe that method was an important factor in our approach. I will return to this point when I consider the impact of x-ray astronomy on astronomy as a whole.

3.1. Plan

Scientifically the discovery of Sco X-1 opened up new horizons. The x-ray flux from this object was 1000 times the flux in the optical domain, and its intrinsic x-ray luminosity was 1000 times the luminosity of the Sun at all wavelengths. Thus we had found some new process of x-ray generation and some new type of star. The fact that such new and unexpected results could be obtained with relatively simple instrumentation opened the field to a large number of astronomers all over the world to further investigate the high energy Universe.

My group at AS&E at this point found itself in a rather difficult situation. The Air Force was no longer willing to support our research, which was pure astronomy. NASA on the other hand had not yet started to support AS&E research on stellar emission. Herbert Gursky and I decided that NASA Headquarters would not support our research unless we proposed a well thought out 5 year plan (1964 to 1969), which included both rocket and satellite instruments and which would be appropriate to advance the field. We were back to the "Plan" phase.

We submitted this new program on September 25, 1963 when only three sources were known, Sco X-1, the Crab Nebula and Cygnus (Giacconi & Gursky 1963).

The plan included a scanning satellite which became UHURU in 1970 and a 1.2 meter diameter x-ray telescope, which after a long obstacle course became CHANDRA, launched in 1999 and still operating today, (Fig. 7).

The 1.2-meter mirror was proposed to achieve sufficient sensitivity to image discrete sources or the granularity of the background on the scale of 1 arc minute, (Fig. 8).

3.2. Execution (Do)

The path that was followed in the execution of the program is illustrated in Fig. 9, showing the steps, which had to be realized to reach CHANDRA. The only project in this figure

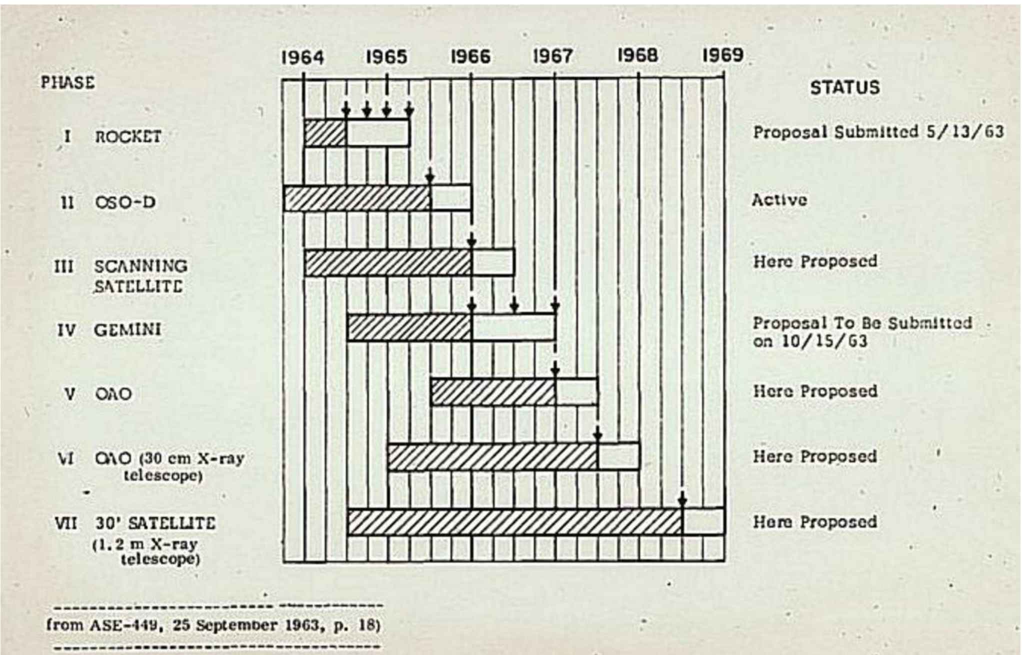

Fig. 7. Time-line for the 1963 AS&E proposal to NASA for an x-ray astronomy program.

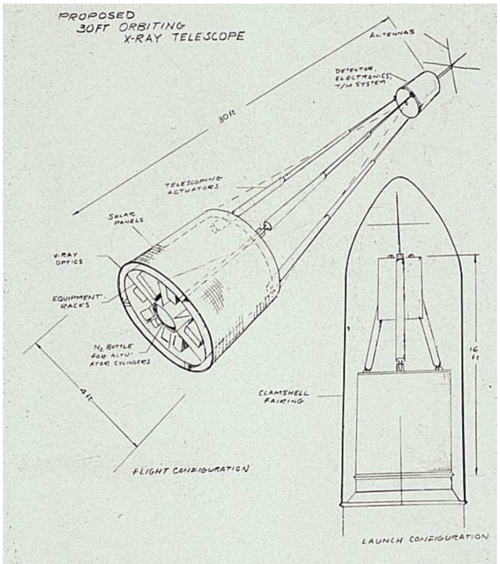

Fig. 8. Sketch of the 1.2 meter x-ray telescope that would eventually, many years later, become the Chandra X-ray Observatory (nee AXAF).

that was not executed was the use of LAMAR optics on a large observatory. Notwithstanding the many recommendations to NASA by several review committees it could never be turned into reality.

As I already mentioned this program led to the use of a 30 cm diameter telescope on SKYLAB for an extended solar study from May 14, 1973 to November 16, 1973. The high angular resolution (< 5 arc sec) and the opportunity to study several solar rotations led to a fundamental change in our understanding of the physics of the corona as discussed by Vaiana and Rosner (Vaiana & Rosner 1978).

In 1970 NASA approved a program for a Large Orbiting X-ray Telescope for extra solar x-ray astronomy, which included a high resolution (Wolter type I) 1.2 meter diameter telescope and a 1 meter (Kirkpatrick-Baez) high throughput mirror. In 1973 the program was canceled due to overruns in other NASA programs.

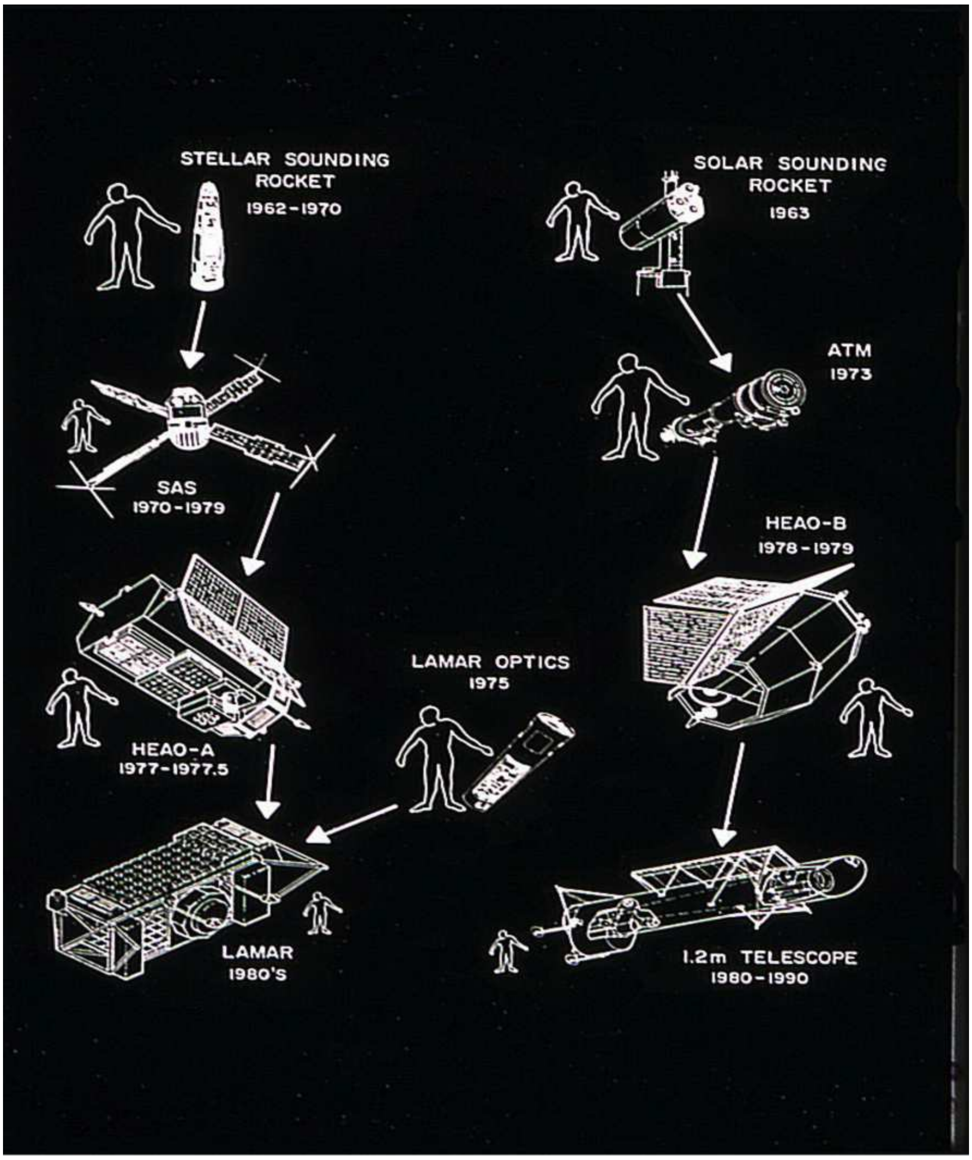

Fig. 9. The path to Chandra as envisioned in 1980. Two parallel paths were taken. On the left non-imaging missions to increase the census of sources and better locate them, and on the right the development of x-ray telescopes.

As part of the High Energy Astronomy Observatory (HEAO) program, a smaller version of the x-ray observatory consisting of a single 60 cm diameter telescope, consisting of 4 nested pairs, was designed, built, and tested in 5 years and flown in 1978. It became known as EINSTEIN and it opened up x-ray astronomy to the study of all celestial objects. We were able to study in their x-ray radiation auroras on planets, forming young stars, all main sequence stars, normal galaxies and active galaxies, clusters of galaxies and the x-ray background (Fig. 10).

To facilitate the use of these new data by all astronomers, several new practices were introduced: I) 30% of the time was reserved for observations by guest astronomers. II) To permit analysis of the data by astronomers not trained in x-ray astronomy, our group at the Harvard-Smithsonian Center for Astrophysics provided the community with calibrated data already transformed in physical quantities. This represented a radical increase in the responsibility typically taken over by an observatory. Rather than just granting guest observers time, we committed ourselves to provide them with data suitable for further analysis. This change was part of the overall Science System Engineering approach (Learn–Think–Plan–Do), which x-ray astronomers pioneered and then introduced, in the scientific operations of NASA Hubble Telescope, in the design, fabrication and operations of the ESO Very Large Telescope and NASA's Chandra. This methodology is now adopted in all of astronomy and I will describe its origin and content in a brief appendix.

3.3. Chandra

After many iterations (and versions), NASA finally accepted the 1976 proposal by H. Tananbaum and me for a 1.2-meter telescope, which was flown in 1999, and is still operating today. It is the most powerful x-ray observatory ever placed in orbit, and its collecting area and exquisite angular resolution (0.5 arcsec) has led to a number of important discoveries. To mention only one as an example it permitted the solution of the problem of the origin of the extragalactic x-ray background first discovered in 1962.

The picture of the Chandra Deep Field South (Fig. 11) was obtained with an exposure of about one million seconds. The total sky area surveyed is only 14x14 arc minutes and contains 346 x-ray sources, or about 1.7/square arc minute. The x-ray flux from these sources is about 10 billion times smaller than that from the source Sco X-1 discovered in 1962 (Fig. 12). Thus x-ray astronomy has progressed in 40 years as much as optical astronomy in 400.

4. The Future

Contrary to the point of view expressed by several astronomers, I am confident that we still are in a discovery era. Given that the physical nature of 97% of the matter in the Universe is still unknown, I believe there is ample room for frontline research that will provide as many surprises as have occurred in the last decades. I think that 2012 is similar to 1609 when astronomy posed many of the unsolved questions, which physics had to solve.

We have learned in the last 50 years that high-energy phenomena are key to structure formation and evolution, and that they are the norm not the exception in the Universe. Whenever we study explosions, high temperature plasmas or high-energy particles, x-ray observations have shown to be essential to their understanding and have provided a powerful and unique tool for their study. It also is important to keep in mind that most of the baryonic matter in the Universe is to be found in high temperature plasmas.

In this article I have tried to explain that the successes of x-ray astronomy were not a fluke, but the result of the bounty of Nature, the aspirations of many people, a fairly rigorous and methodical research effort, and the development of new technology and new operational approaches. In the last 50 years we have made great steps in our physical understanding of what the x-rays have shown us, we have made a progress of 10 billions in sensitivity and we have developed the know-how and the methods to build even more powerful observatories.

I am therefore certain that in the next 50 years x-ray astronomy will reach new heights. I hope the new generation of astronomers will have the opportunity to Learn-Think-Plan and Do as we have had.

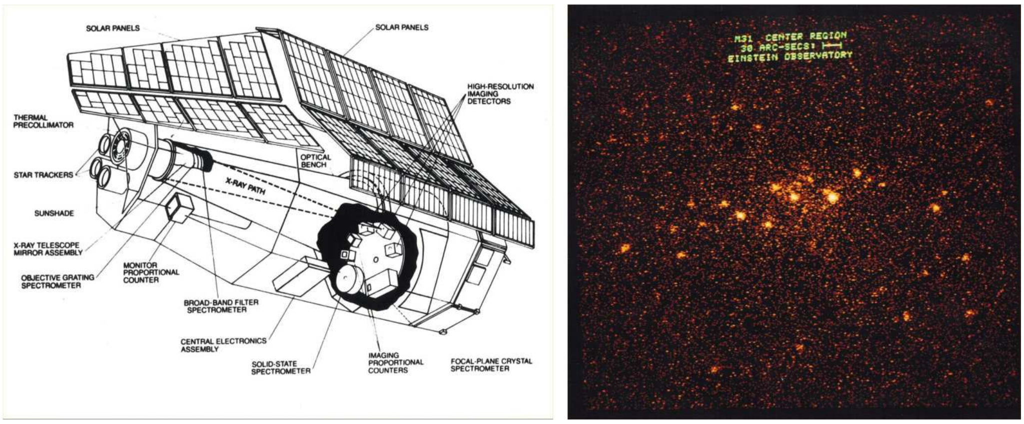

Fig. 10. On the left is a sketch of the Einstein X-ray Observatory (aka HEAO-B) which contained a 0.6 m diameter X-ray telescope. On the right is an image of the nuclear region of the Andromeda Galaxy (M31) resolving the emission from individual binary systems, similar to those in the Milky Way.

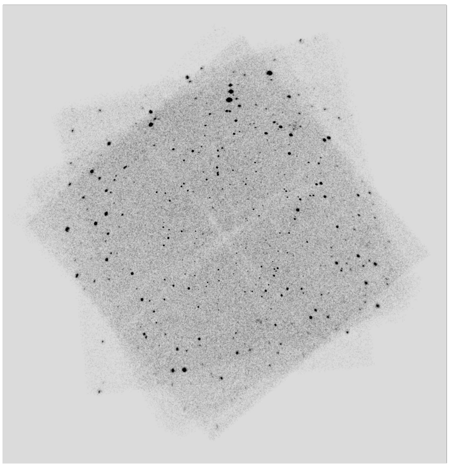

Fig. 11. The Chandra Deep Field South 1 Msec image.

Acknowledgements. I am grateful to Stephen Murray for his lively discussions regarding the history of the field and the practice of science systems engineering. Steve was very helpful in preparing both this manuscript and the presentation at the Milano conference. Thanks also to Harvey Tananbaum for his careful reading and thoughtful comments.

Appendix A: The Method

I am well aware that most scientists, including me, do their research with a total disregard of the views of philosophers of science. When I refer to method, I mean something more modest and practical, namely what we have come to call Science System Engineering, which has been adopted over the years by my colleagues and myself in x-ray Astronomy and then transferred to optical Astronomy. Stephen Murray is teaching it as a course at JHU. As a mnemonic aid to myself I describe the method simply as LEARN–THINK–PLAN–DO (and TEACH).

I first learned it from a great particle physicist Robert W. Thompson, who established, with a magnetic field cloud chamber, the existence of the theta zero meson by measuring its mass to be 971+/- 10 electron masses as he reported at the Congress of Bagneres de Bigorre in 1953 (Thompson, Buskirk & Etter 1953).

I was shipped to work with him at the University of Indiana in 1956, by my colleague and mentor Beppo Occhialini as a Fulbright Fellow. Thompson's report, which I had studied in the Proceeding of the Conference, had impressed me for its clarity and precision, and I became convinced that none of the other cosmic ray groups could compete with his work.

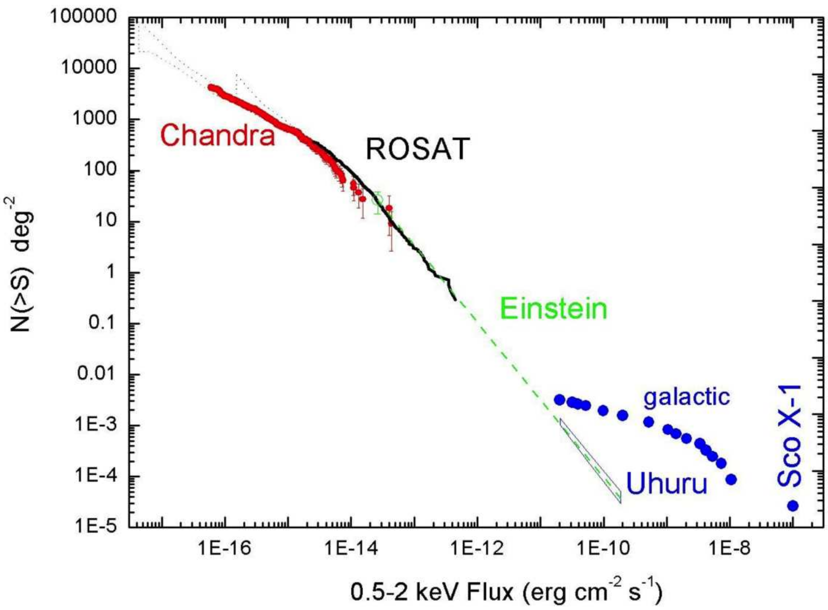

Fig. 12. The logN-logS distribution of x-ray sources from the brightest Sco X-1 to the faintest seen in the 1 Msec CDFS. The extended CDFS 4 Msec data extend the faintest source flux to $\sim 10^{-17}$ about 10 billion times fainter than Sco X-1.

Thompson had defined the physics problem he wanted to solve, designed and constructed the necessary instruments including the cloud chamber, the magnet and the stereoscopic optics that allowed the required precision for the measurement of momentum of the particles from their tracks. He developed the data reduction and analysis process, including the careful calibrations, the painstaking error determination and the methodical streamlining of the computation to a degree I had not yet encountered. In effect he had applied what we would call today an end-to-end analysis to the entire work. I learned and used all of these techniques and I used his data for a search of the anti-lambda zero particle, unsuccessful because of the scarce statistic. I find in retrospect that his teaching has guided me throughout my work.

The method consists simply in: I) learning what has been done in the field so far, including theory, observational research and techniques. II) In thinking very carefully and critically about previous experimental work in the field, and trying to come to some conclusions about the potential for significant new discoveries. To analyze one's strength and weakness in actually executing the necessary work. To consider the difficulty and length of the technical effort required and commit to it. To carry out gedanken experiments to determine by simulation the required absolute and statistical accuracy in the measurements. The influence of the external known conditions and backgrounds in making the analysis more complicated. III) Plan how to bring the experiment to conclusion as to time, resources and help required. IV) Do. Execute the plan using best available technology, skills and management to achieve results as quickly and as cheaply as one can. None of this can be done in a large program, were many people are involved, unless they share in the vision of what has to be done, and consider its overall goal as their own. Communication up and down and sideways is essential. Honest criticism of each others work is essential and should be welcomed not rejected.

It is fair to say that my colleagues and I followed this approach during most of our work without feeling a need to write it down or document it at AS&E, CFA, STScI, and ESO. At AS&E we simply assumed that everybody worked that way. In 1973, at CFA we found that most astronomers did not, and we were simply carrying on with what we called the UHURU spirit. At STScI (Space Telescope Science Institute) Ethan Schreier, Rodger Doxsey, Don Hall and I had the chance to start a whole institution from zero and, interpreting the views of the Horning Committee, we decided that we had to satisfy the needs of the astronomy community, as we best understood them. We were helped by the advent of computers in producing a rather sophisticated Science Operation System that was end-to-end from proposal support to in-flight operations, calibration, sequence of observations, on-line data reduction and finally random access archive. Much of the work was made possible by automated systems. The preparation of a new all sky catalog of stars brighter than 15th magnitude prior to launch to permit pointing of Hubble efficiently is an example of how we approached the science requirements.

At ESO we applied this same method to the entire design, fabrication, testing and operation of the Very Large Telescope as well as the end-to-end data handling system as I described in Secrets of the Hoary Deep (Giacconi 2008).

This changed view of the responsibility by an observatory staff has permitted quick utilization of the data from major observatories and the ability to make repeated use of archival data by many users. Most of the results have been good, except for a separation between builders and users, which I believe is not healthy for the field. Particular attention is needed to insure the training in "LEARN–THINK–PLAN–DO" of the new generation of astronomy.

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