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The Chandra X-ray observatory

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Abstract. This paper describes a brief history of the development of the Chandra X-ray observatory, based on the talk which was presented on October 17, 2010 at the Chandrasekhar Centennial Symposium held in the campus of the University of Chicago.

Keywords : X-rays: general – telescopes – space vehicles: instruments

1. Introduction

First, I would like to thank the organizing committee for inviting me to this very interesting conference. Nobel laureate Subrahmanyan Chandrasekhar is certainly deserving of such an accolade. I would like to turn from the theoretical topics that have occupied most of today's lectures, to a more experimental topic, that of the history of the Chandra X-ray Observatory. This Observatory was built to explore the high energy Universe which features such exotic objects as neutron stars and black holes. Chandra was very interested in black holes as is illustrated by his description that "The black holes of nature are the most perfect macroscopic objects there are in the Universe: the only elements in their construction are our concepts of space and time." One of the closest examples of a massive black hole is the one at the centre of our Galaxy in SgrA* shown in Fig. 1 from a 500 ks Chandra image obtained by Muno et al. (2003). This remarkable object is emitting X-rays at a rate of only 2×10^{33} ergs/s which is nearly nine orders of magnitude below that of an active galactic nucleus (AGN). One interesting feature of this object is the flaring activity that was detected by Chandra (Baganoff et al. 2001). These flares occur aperiodically with a frequency of approximately once per day and represent increases of up to a factor of one hundred in luminosity for up to an hour in duration.

A brief outline of the paper is as follows which describes different phases of its history in the

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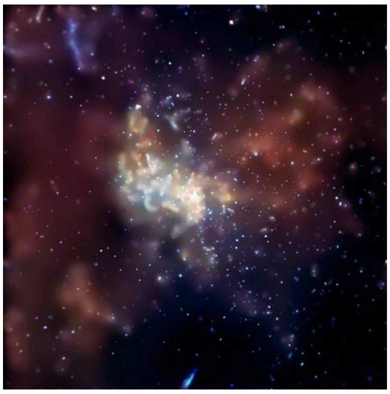

Figure 1. The 16 arcmin square region of the Galactic Centre with SgrA* at the centre of the image was obtained from a 500 ks exposure using the Chandra X-ray Observatory (Chandra archives at http://chandra.harvard.edu/photo/2003/0203long).

following Sections: a brief history of the Observatory; the early years; the big test; construction at last; testing; launch. The last Section describes a few results.

2. A brief history of the Observatory

The idea of building an X-ray telescope was advanced by Riccardo Giacconi and Bruno Rossi in a seminal paper in 1960 (Giacconi & Rossi 1960). The idea used grazing incidence X-rays on highly polished metal surfaces shaped into paraboloidal and hyperboloidal shapes to form a sharp image. A schematic diagram of this concept is shown in Fig. 2.

Following the discovery of an extra-solar X-ray source in 1962 (Giacconi et al. 1962), Giacconi and his collaborators at American Science and Engineering proposed a program of X-ray astronomy to NASA which included a large focusing X-ray telescope of 4 feet (1.2 m) with a focal length of 30 feet ($\sim$10m) in 1963 and an angular resolution of about one arcmin. NASA accepted the Sounding Rocket portion of the proposal but deferred on the large telescope. In 1968 NASA initiated the High Energy Astrophysics Program of four large observatories to cover the field from X-rays to high energy cosmic rays which included a 1.2 m diameter X-ray telescope. The program was cancelled in 1973 by NASA and reconstituted as a much smaller program that included a 0.6 m X-ray telescope which became the Einstein Observatory in 1978. In 1976 Dr. Riccardo Giacconi and Dr. Harvey Tananbaum, then at Harvard, submitted a letter proposal to NASA to begin the study of a 1.2 m diameter X-ray observatory. NASA accepted the idea and organized a study group to define the observatory. In order not to call attention to the fact that this was another large observatory program being initiated by NASA like the Hubble Telescope, the group decided to call the observatory the Advanced X-ray Astrophysics Facility to make it sound less expensive. In 1985 four focal plane instruments and two grating designs were selected for study. These included the High Resolution Camera, the Advanced CCD Imaging Spectrom-

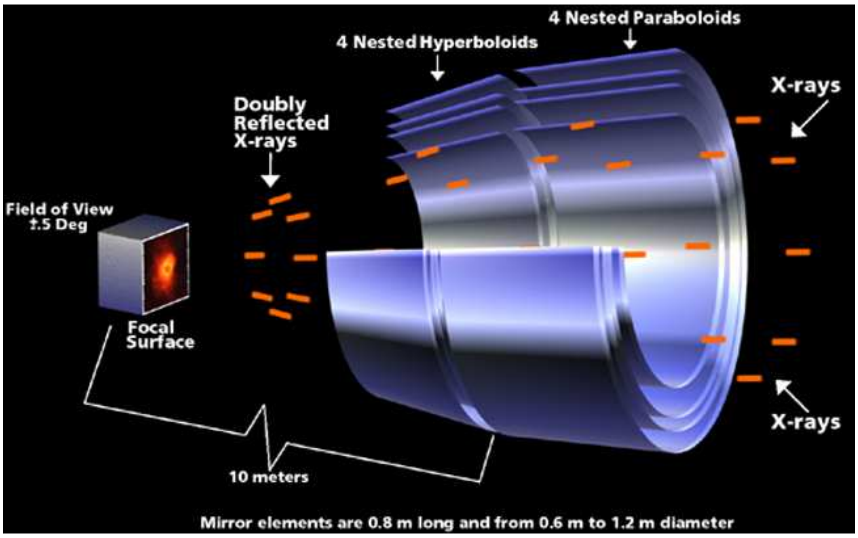

Figure 2. Schematic representation of the Giacconi-Rossi concept as applied to the Chandra X-ray Observatory mirrors. In Chandra the focal surface contains the High Resolution Camera and the Advanced CCD Imaging Spectrometer on a translation table (http://chandra.harvard.edu/graphics/resources/illustrations/cxcmirrors-72.jpg).

eter to the AXAF CCD Imaging Spectrometer (later changed to the Advanced CCD Imaging Spectrometer after the name Chandra was chosen for the Observatory), the Bragg Crystal Grating Spectrometer and the X-ray Calorimeter together with the Low Energy and Medium/High Energy objective transmission gratings. The observatory was to be in low earth orbit and be serviced by the Space Shuttle astronauts. The instruments were designed to be changed out for new improved instruments as new technology became available.

3. The early years

Even though instruments had been selected and a spacecraft contractor was selected shortly thereafter, there was no guarantee that the program would receive a ‘New Start’ by Congress. The AXAF program received the highest ratings in the 1980 and 1990 Decadal Surveys by the astronomical community, but Congress was reluctant to fund a program with such a high technical risk, that of producing 0.5 arcsec X-ray mirrors which were better than any mirrors made thus far by an order of magnitude. Dr. Charles Pellerin, director of the NASA Astrophysics Division, proposed a clever way to sell the program. By combining the Hubble Space Telescope, the Compton Gamma-Ray Observatory, AXAF and the Space Infrared Telescope into a Great Observatories Program (a name suggested by George Field) he produced a package that was more saleable to Congress. To put the Congressional staffers at ease, a bargain was made to make the largest mirror and test it to prove that the technology was up to the challenge. If the mirror failed the test, then the program would not go forward. In 1991 the largest of the AXAF mirror pairs was

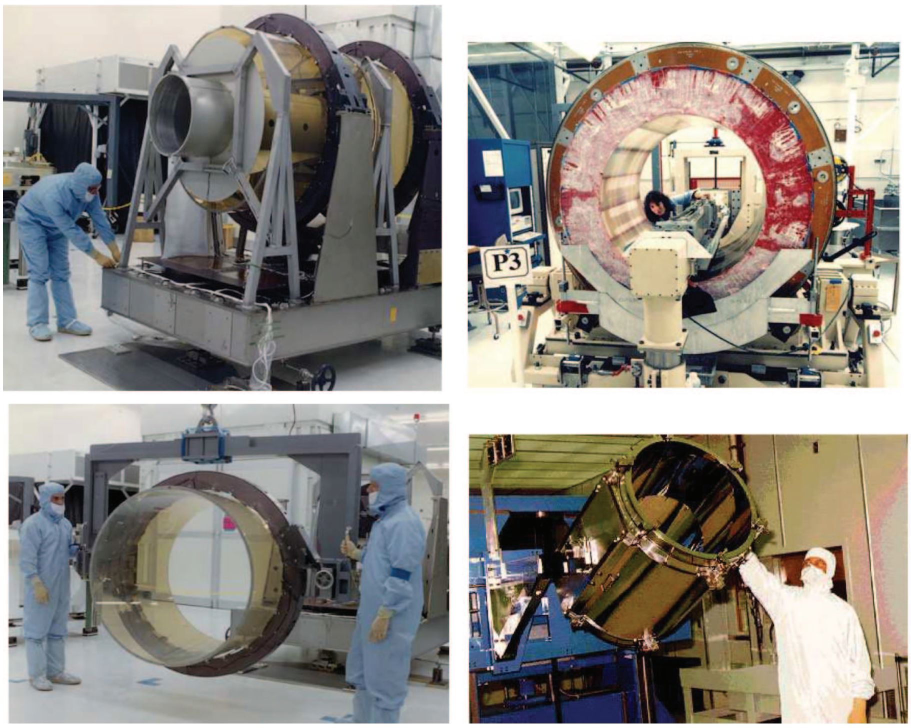

Figure 3. Upper left: The mirror assembly being readied for testing at the MSFC testing facility (http://chandra.harvard.edu/graphics/resources/illustrations/veta7_72.jpg); upper right: the polishing process at HDOS (http://chandra.harvard.edu/graphics/ resources/illustrations/presentPolish1-72.jpg); lower left: the completed P1 mirror before coating it with Iridium (http://chandra.harvard.edu/ graphics/resources/illustrations/2c_mounted_primary.jpg); lower right: one of the AXAF mirrors after the coating process (http://chandra.harvard.edu/graphics/resources/illustrations/barrel.jpg).

completed and ready for testing after a tremendous effort by the Telescope Scientist, Dr Leon van Speybroeck, and the mirror fabricators at Hughes Danbury Optical Systems (HDOS). Dr. Martin Weisskopf, the AXAF project scientist, and Danny Johnson, the Project Engineer, were in charge of the design and construction of the testing facility at Marshal Space Flight Center (MSFC), which they successfully completed in time for the X-ray testing of the mirror pair. The testing revealed that the mirrors sagged in the 1g field of the test facility and special fixturing had to be created to remove the effects of gravity on the mirrors. Once this was done, the mirrors passed the test with flying colours. Fig. 3 shows the mirrors ready for testing at the MSFC facility.

Although the mirror test had been successful, the program was still not out of the woods. The Super Conducting Super Collider had experienced very significant over runs in its budget and was cancelled in 1992. The Space Station was also experiencing very large over runs in costs. Attempts within NASA to cancel the Space Station failed in Congress and NASA was told to proceed using what money it had with no budgetary increases. This placed severe constraints on the science budget. The Office of Management and Budget (OMB) had projected that the AXAF program would have a total run out cost in excess of 6 billion dollars, making it a target for cancellation as well. Charlie Pellerin at NASA HQ called a meeting to discuss ways to reduce the cost of AXAF and to control the run out costs of the mission. The Hubble Space Telescope was alerting Congress to the very substantial costs of servicing a mission in low Earth orbit. There was some reluctance among the AXAF scientists to descope AXAF, but a presentation by Leonard Fisk, the Associate Administrator of NASA, convinced the group that descoping was the only way to keep the program alive. The decision after much debate was to reduce the number of mirror pairs from six to four and to carry only the two focal plane instruments which could be used for enhanced spectroscopy by employing the objective gratings behind the mirrors to produce a dispersed spectrum. In consultation with TRW, the prime contractor, and the instrument teams, the observatory was redesigned to go to a high Earth orbit that could not be serviced by the Space Transportation System, thereby guaranteeing that there would be no mission servicing costs. With this change of design, Congress agreed to fund the construction of the observatory. In order to salvage the higher resolution spectroscopy portion of the mission, a second mission called AXAF-S was designed to carry the high-resolution calorimeter and Bragg crystal spectrometer. Unfortunately, after a preliminary design of this mission, it was cancelled.

4. Construction at last

In 1993 the program went into high gear. The mirror facility at the Hughes Danbury Optical Systems plant began the process to grind, figure and polish the remaining three mirror pairs. The polishing process is illustrated in Fig. 3, where the axis of the mirror is nearly horizontal and narrow shaping and polishing tools are used to polish and figure the surface between metrology measurements in the metrology facility, specifically designed for the AXAF mirrors.

The creation of the AXAF mirrors, which are an order of magnitude more precise than any such mirrors ever made, are the result of the leadership and ability of the Telescope Scientist, Dr. Leon van Speybroeck of the Center for Astrophysics at Harvard and the dedicated and skillful engineers and opticians at HDOS. After the mirrors were figured and polished and tested at HDOS they traveled to the Optical Coatings Laboratory Inc (OCLI) in Santa Rosa, CA, where they were coated with Iridium to provide the highest reflectivity at X-ray wavelengths. One of the mirrors is shown in Fig. 3 at the OCLI facility. Following the coating of the mirror surface the mirrors were shipped to Eastman Kodak where they were assembled into a holding fixture that provided the accurate alignment of the mirror pairs to complete the High Resolution Mirror Assembly (HRMA). This process is shown in Fig. 4.

This process was crucial to the formation of a high quality image. Each mirror pair must focus to the same point to provide a sharp image. Unfortunately, the inner mirror pair slipped slightly in the gluing process so that a ghost image was formed about one half arc second away from the focus of the other mirror pairs. Since this was the smallest mirror pair with the least area at the lower energies, this image is not usually apparent. It can be detected if a source is piled up

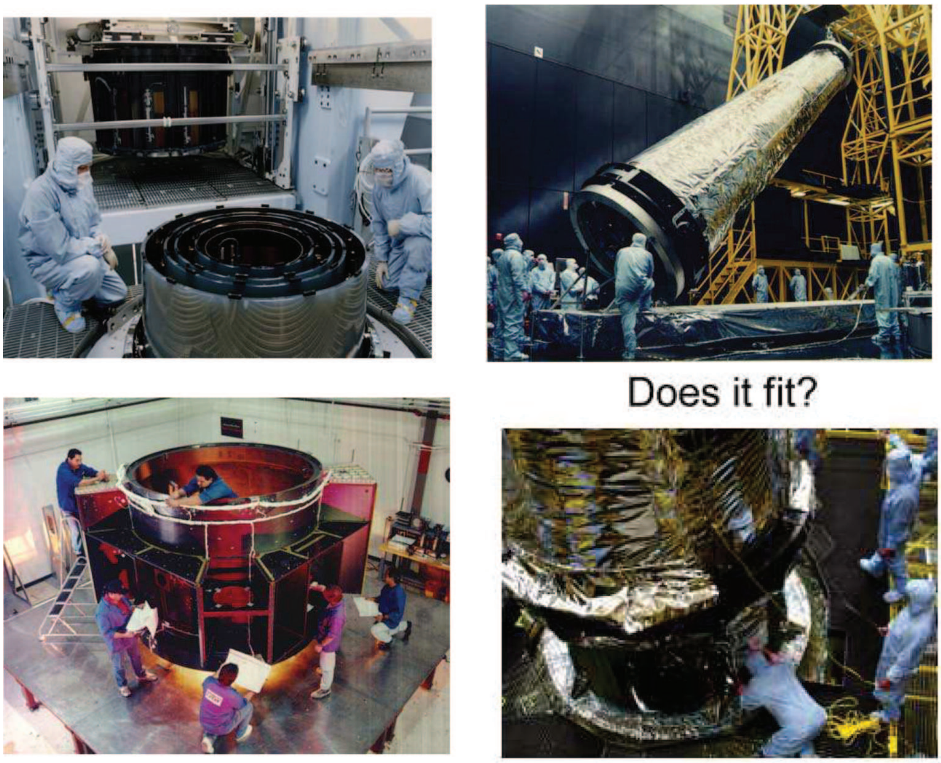

Figure 4. Upper left: The fabrication of the High Resolution Mirror Assembly (HRMA) at Eastman Kodak (http://chandra.harvard.edu/graphics/resources/illustrations/hrma_11.jpg); upper right: the carbon fiber epoxy telescope tube covered with a protective coating (http://chandra.harvard.edu/graphics/resources/illustrations/craftOptBench45-72.jpg); lower left: the epoxy structure of the spacecraft at TRW's Space and Electronics Group. This material was adopted to reduce the weight of the AXAF (http://chandra.harvard.edu/graphics/resources/illustrations/craftBusRed1-72.jpg); lower right: The telescope being inserted into the spacecraft (courtesy of Robert Burke and Blake Bullock of Northrop Grumman Aerospace Systems).

in the primary image, thereby reducing the intensity of the center of the image and revealing the fainter image from the inner pair of mirrors which is not piled up. The optical bench or telescope tube was fabricated at Kodak as well as the HRMA. This large carbon fiber epoxy structure is shown in Fig. 4. The telescope tube was not baked to reduce the volatiles that were trapped in the matrix. These volatiles slowly escaped after the telescope was in orbit and may have been part of the reason that the cold filter of the Advanced CCD Camera was slowly coated with an unknown layer of material. The spacecraft was designed, assembled and tested at TRW Space and Electronics Group (now part of Northrop Grumman Aerospace Systems). Fig. 4 shows the spacecraft under construction at the Redondo Beach, CA facility of TRW. The telescope tube and

HRMA were brought together in the spring of 1998. Fig. 4 shows the mating of the telescope to the Observatory.

5. The instruments

The scientific instruments for AXAF consist of two focal plane cameras, the High Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS) as well as two objective transmission grating assemblies located just behind the mirrors. The objective transmission gratings were the responsibility of the two Principal Investigators, Dr. Claude Canizares of MIT for the high and medium energy transmission gratings, and Dr. Albert Brinkman of the Space Research Organization of the Netherlands for the low energy transmission grating. The HRC team was led by Dr. Steven Murray of the Center for Astrophysics at Harvard, and the ACIS team was led by Dr. Gordon Garmire of the Pennsylvania State University.

The objective transmission grating were challenging to construct in that they were extremely thin and had to be self supporting in order to transmit the lowest energy X-rays as well as survive the high acoustic levels encountered during a Space Shuttle launch. I don't have time to go into the details of the fabrication process other than to say that it uses high resolution lithography. An example of a completed grating assembly is shown in Fig. 5.

The High Resolution Camera employed micro-channel plates similar to the Rosat and Einstein Observatory high resolution imagers. A large micro-channel plate formed the imaging array and three smaller plates formed the spectroscopic array imager. The micro-channel plates used 10 micron pores which formed the limiting spatial resolution of the camera. With the 10 m focal length of the HRMA this provided an angular resolution of about 0.2 arcsec on the sky, over sampling the point spread function of the HRMA which is about 0.5 arcsec. The HRC does not provide a very accurate determination of the X-ray energy, but when combined with the transmission gratings, particularly the low energy grating, it can achieve an energy resolution $E/\Delta E$ of about 1000. Another advantage of the HRC is that it provides 16 microsecond time resolution for the X-ray events for sources that are positioned on the central micro-channel plate of the spectroscopy array and are below the telemetry saturation level. Fig. 5 (upper right) shows a picture of the HRC and Fig. 5 (lower left) shows the completed HRC with its electronics ready for mounting on the translation table that moves the camera in and out of the focal plane of the HRMA.

The ACIS instrument employs CCDs as the basic detecting element. The CCDs for ACIS, which were fabricated by MIT's Lincoln Laboratory, are of two types: front illuminated and back illuminated. Front illuminated CCDs expose the portion of the silicon chip that the CCD is constructed on that is covered by the readout gates and insulators. This limits the lowest energy that the CCD can detect to about 0.4 keV with a small narrow (in energy) window at 0.25 keV. The depth of the depleted silicon under the gate structure is about 50 microns, which results in a upper energy cut-off at around 8 keV. The energy resolution of the CCD varies from about 100 eV at 1 keV to about 160 eV at 6 keV. The back illuminated CCD has been thinned to about 40 microns

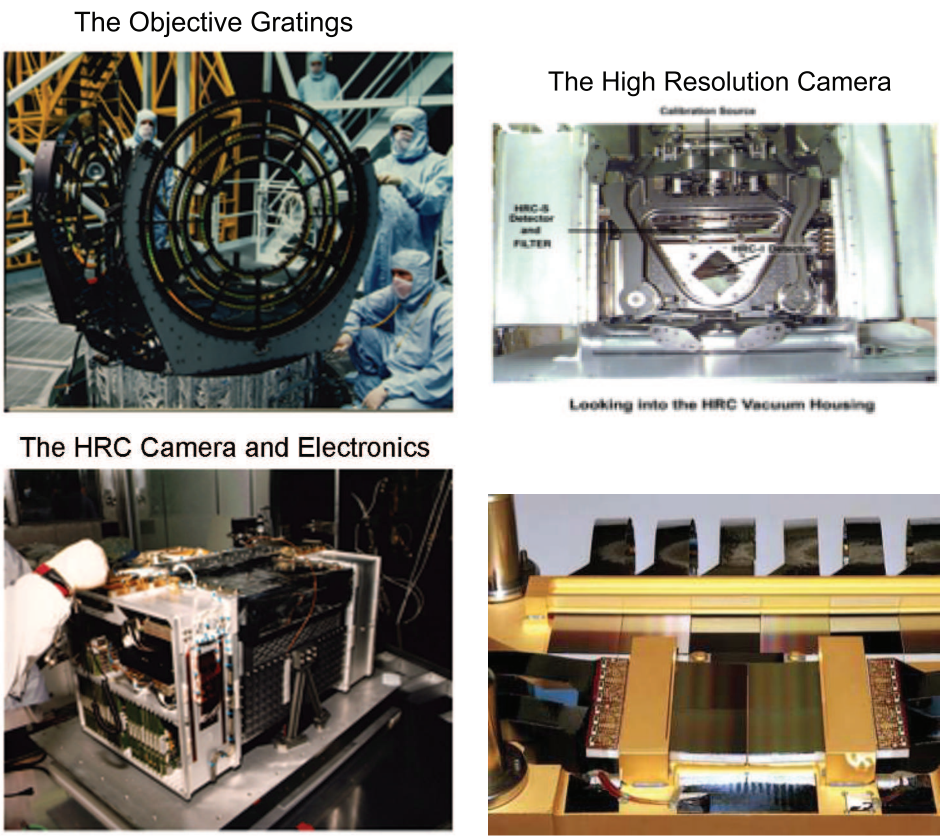

Figure 5. Upper left: The objective transmission grating assembly mounted behind the HRMA. Either the high and medium transmission gratings or the low energy transmission gratings can be rotated into place behind the HRMA to provide a dispersed spectrum of the object under study (http://chandra.harvard.edu/graphics/resources/illustrations/gratingsLow1-72.jpg); upper right: The High Resolution Camera as observed from the HRMA (http://chandra.harvard.edu/graphics/resources/illustrations/HRClabel-72.jpg); lower left: The HRC with its electronics assembly ready for mounting to the translation table (http://chandra.harvard.edu/graphics/resources/illustrations/HRCbox-72.jpg); lower right: The ACIS array of 10 CCDs. The four CCDs in the square array are the imaging array front illuminated CCDs and the six CCDs in a linear array form the spectroscopic array to image the spectrum dispersed by the transmission gratings. The two mirror surface CCDs are the back illuminated CCDs. The gold colored bars across a portion of the CCDs are radiation shields to prevent X-rays from impinging upon the frame store portion of the CCDs. The optical blocking filters are not shown in this view (Courtesy of MITs Lincoln Laboratory, Bernie Kosicki).

thick and the readout gate structure is away from the incoming X-rays such that the incident X-rays fall on the thinned silicon layer that is only covered by about 0.03 microns of a special backside treatment. This increases the quantum detection efficiency of the back illuminated CCD to about 60% at 0.25 keV. The CCDs must be covered by an optically opaque film to prevent them from responding to visible light which is focused by the HRMA onto the focal plane. The polyimide plastic film, provided by the Luxel Corporation, that is 2000 Angstroms thick and coated by 1600 Angstroms of aluminum covers the four front illuminated CCDs comprising the imaging array. The spectroscopic array of 6 CCDs, two of which are back illuminated, is covered by the polyimide film of the same thickness and a 1300 Angstrom aluminum film. Over the course of the mission, a slow buildup of some form of contaminant has coated the filter, decreasing the low energy efficiency of the ACIS instrument. By using the onboard calibration source, it has been possible to measure this buildup and correct the quantum efficiency accordingly. A picture of the ACIS CCD array is shown in Fig. 5 (lower right). The completed ACIS instrument with its electronics is shown in Fig. 6.

The CCDs are read out every 3.24 seconds in their normal mode of operation. Special modes, such as using a reduced numbers of CCDs or using only a portion of a CCD, can reduce the sample time to 0.2 seconds. Continuously clocking of a CCD can reduce the sample time to 3 milliseconds but one loses a spatial dimension of the image. The pixel size is 24 microns resulting in an image with a sampling every 0.492 arc second, about the same as the point spread of the HRMA.

Several problems developed during the construction of the ACIS instrument. During the assembly of the flight unit focal plane array, it was discovered that the flex prints that carry the voltages and clocking signals to the CCD and the data stream from the CCDs were failing. The printed-through holes in the circuit boards attached to the CCDs were cracking and creating open circuits upon thermal cycling. This was a major problem, since the flight unit used these boards and they would have to be debonded from the CCDs and replaced. A company was found called Speedy Circuits that could quickly supply new boards that could survive the thermal cycling. The company said you can have two of the following three choices: quick delivery; reliable units; or low cost. Obviously at this point we opted for the first two choices.

6. Testing

The delays caused by the flex print problem made it impossible to provide the finished camera in time for the calibration of the instruments at the Marshall Space Flight Center in Huntsville, Alabama which was scheduled in March through May of 1997. ACIS provided a “two chip” camera for the calibration to at least see how the CCDs would perform in the focal plane of the HRMA. The full ACIS arrived in Huntsville after the HRMA was taken to TRW for integration into the spacecraft. This calibration in the facility did provide some useful information about the CCDs in a calibrated X-ray beam. The setup at the calibration facility is shown in Fig. 6. The ACIS instrument travelled to Ball Brothers Research Center in Boulder, CO next for integration onto the translation stage that carries the two cameras into the focal plane of the HRMA. The translation stage is shown in Fig. 6 (lower right).

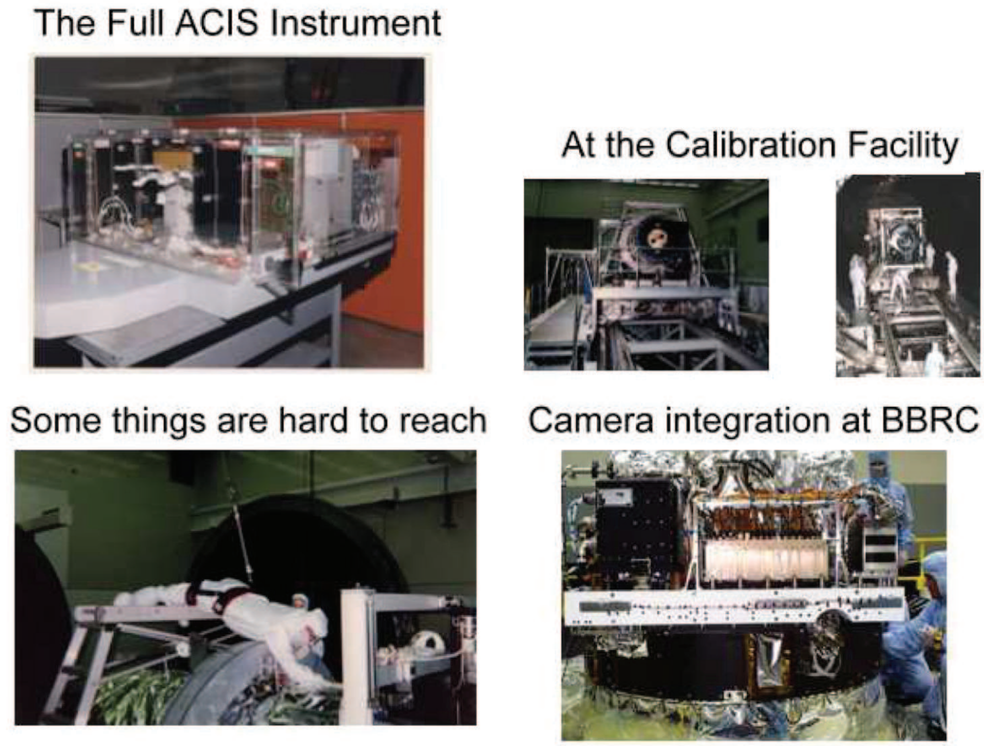

Figure 6. Upper left: The complete ACIS camera and electronics assembly. The white straps are thermal conductors which will be connected to radiators on the spacecraft to cool the CCDs and camera housing (Courtesy of Ball Brothers Aerospace Corporation); upper right: The HRMA being prepared for insertion into the vacuum chamber at the MSFC test facility (photo courtesy of Robert Burke, Northrop Grumman Aerospace Systems); lower left: Making some adjustments to the HRMA mount at the MSFC test facility (Courtesy of Robert Burke, Northrop Grumman Aerospace Systems); lower right: The instruments being assembled and tested at BBRC (http://chandra.harvard.edu/graphics/resources/illustrations/modul1-72.jpg).

The next step was to integrate the translation table and instruments with the telescope and spacecraft at TRW (Fig. 7). The next major problem encountered, besides the difficulty of producing high quality CCDs, especially the back illuminated versions, was encountered during the vacuum test of the full Observatory at TRW (Fig. 7, upper right). In order to verify that there were no light leaks that might degrade the CCD operation on orbit, the protective vacuum sealed door covering the CCDs and filter had to be opened in the vacuum chamber and lights shown onto the spacecraft to simulate solar, lunar and Earth shine illumination. When the command was given to open the door, the mechanism failed and the door did not open. There was no way to open the door with this kind of failure. The only remedy for this problem was to remove ACIS from the Observatory and return the unit to Lockheed Martin Aerospace Corp., where the door was designed and fabricated, for testing and redesign as needed. After extensive testing, no failure

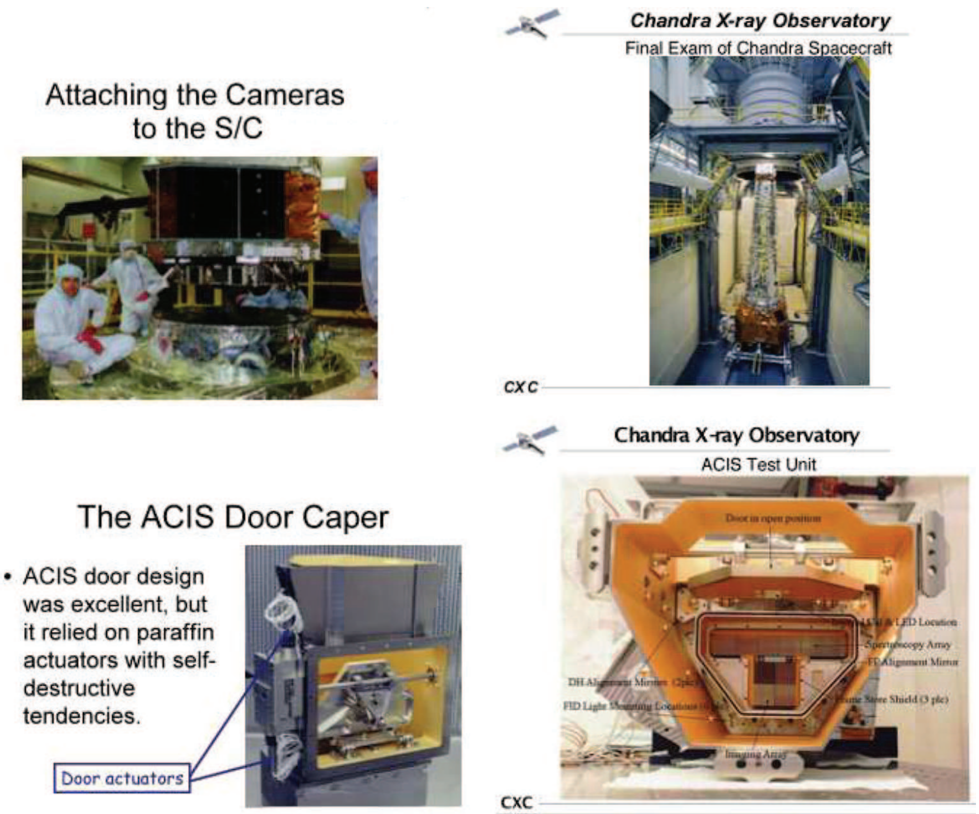

Figure 7. Upper left: Mating the translation table assembly to the spacecraft at TRW (http://chandra.harvard.edu/graphics/ resources/illustrations/obs_assemb7_72.jpg); upper right: The Observatory ready to be lifted into the vacuum chamber for the thermal vacuum testing (http://chandra.harvard.edu/graphics/resources/illustrations/chandaFinalExam-72.jpg); lower left: The ACIS door and door opening mechanism. The horizontal shaft rotates to pull the door into this position, which is the open position. The opposite rotation closes the door against the o-ring seal shown in the lower right panel (Courtesy of Mark Bautz, MIT); lower right: The ACIS camera showing the door, CCDs and the o-ring seal. The camera is under vacuum at launch to protect the thin optical blocking filters from the acoustic load generated by the launch vehicle (http://chandra.harvard.edu/graphics/resources/illustrations/ACISlabel-72.jpg).

mechanism was found that could cause the door to stick shut. Some redesign of the opening mechanism permitted an evaluation of the door opening process so that it might be possible to try opening the door without breaking the opening mechanism and thereby seek solutions to the sticking should it occur on orbit. Thankfully, the door opened without a problem on orbit, but we still do not know what caused the failure at the TRW test. The ACIS door is shown in Fig. 7.

In making a complex observatory there are literally thousands of people involved. I cannot

ACIS Development Team

Penn State	MIT CSR (MKI)		MIT Lincoln Lab
Gordon P. Garmire, IPI	George Ricker, Dep PI	Jim Francis	Bernie Kosicki
	Mark Bautz , Proj. Sci.	Gordon Gong	Barry Burke
John Nousek (Lead Co-I)	Claude Canizares	Dorothy Gordon	Jim Gregory
Pat Broos	Steve Jones	Phil Gray	Al Pillsbury
David Burrows	Steve Kissel	Pete Tappan	
George Chartas	Gregory Prigozhin	Brian Klatt	Lockheed Martin
Eric Feigelson	Herb Manning	Matt Smith	Lloyd Oldham
Scott Kock	Fred Baganoff	Eric Kintner	Neil Tice
George Pavlov	Takashi Isobe	Demitrios Athens	Scott Anderson
Leisa Townsley	Hale Bradt	Beverly Lamar	Ed Sedivy
Eric Cocklin	George Clark	Mike Pivoviraoff	Larry Campbell
Catherine Grant	Saul Rappaport	Mike Doucette	
	Robert Goeke	Fred Kasperian	JPL/Caltech
Carnegie Mellon	Ed Boughan	Dan Hanlon	S. Andy Collins
Richard Griffiths	Rick Foster	Fred Miller	Steve Pravdo
	Peter Ford	Jim O'Connor	Albert Metzger
	John Doty	Ann Davis	Wallace Sargent
		Bob Blozie	
		Ellen Sen	+SAO & MSFC

Figure 8. Left: The ACIS development team and the most of the original co-investigators; right: The complete Chandra X-ray Observatory with the booster rocket attached in the hanger at KSC (http://chandra.harvard.edu/graphics/resources/illustrations/99pp0704-72.jpg).

give credit to all of them in the space here, but I do want to mention all of the people involved in the ACIS experiment. They are given in Fig. 8 (left panel).

7. Launch!

The Chandra X-ray Observatory finally arrived at the Kennedy Space Center in the spring of 1999. Fig. 8 (right panel) shows the full Observatory with the rocket booster attached that will send it into a highly elliptical orbit. The onboard rocket, which is part of the spacecraft, will then increase the orbital altitude and circularize the orbit. Eileen Collins was the Mission Commander, the fist woman to assume this role. After two unsuccessful launch attempts the Space Shuttle Columbia roars into space with the Chandra X-ray Observatory on board. The launch turned out to be a nail biter. Quoted below are the mission notes from NASA.

"During the countdown for launch on the third attempt, a communications problem occurred that resulted in the loss of the forward link to Columbia. The problem was corrected at the Merritt Island Launch Area (MILA) ground facility and communications was restored. As a result of this problem, the time of the planned launch was slipped seven minutes to 12:31 a.m. EDT on July 23.

About 5 seconds after liftoff, flight controllers noted a voltage drop on one of the shuttle's electrical buses. Because of this voltage drop, one of two redundant main engine controllers on two of the three engines shut down. The redundant controllers on those two engines — centre

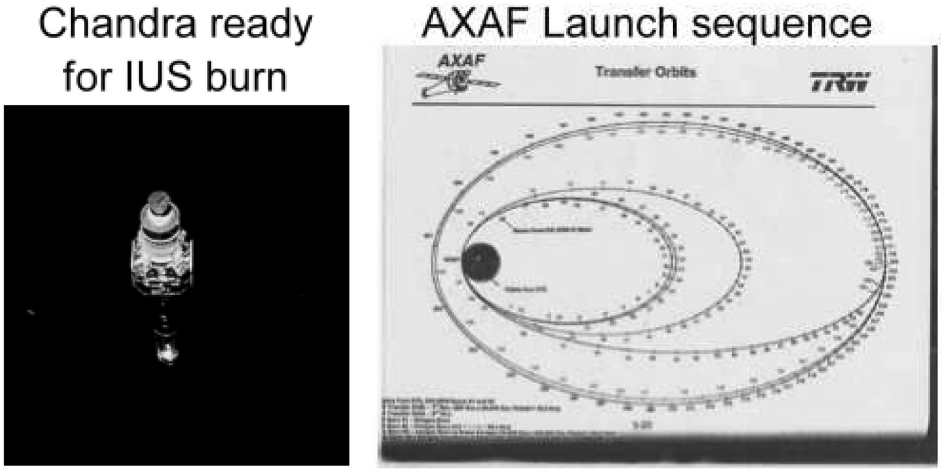

Figure 9. Left: The view of Chandra and its attached booster as it drifts away form STS-93. (http://chandra.harvard.edu/graphics/resources/illustrations/deploy/sts93-deploy1-72.jpg); right: The orbital insertion sequence following the STS-93 launch and ejection of the Observatory from the Space Shuttle (TRW document).

and right main engines — functioned normally, allowing them to fully support Columbia's climb to orbit.

The orbit attained, however, was 7 miles short of that originally projected due to premature main engine cutoff an instant before the scheduled cutoff. This problem was eventually traced to a hydrogen leak in the No. 3 main engine nozzle. The leak was caused when a liquid oxygen post pin came out of the main injector during main engine ignition, striking the hotwall of the nozzle and rupturing three liquid hydrogen coolant tubes.

The orbiter eventually attained its proper altitude and successfully deployed the Chandra X-ray Observatory into its desired orbit." [1]

After the Space Shuttle achieved orbit, the bay doors were opened and the Chandra X-ray Observatory with its attached booster rocket was ejected from the payload bay. Fig. 9 (left panel) shows the last views of the Observatory as it drifts off in preparation for the insertion into a high elliptical orbit. It took almost another week before the Observatory reached its final orbit of 10,000 by 138,000 km, requiring five different burn sequences using the onboard rocket. Each burn was a source of worry. The orbital insertion sequence is shown in Fig. 9 (right panel). Once the final orbit was achieved, the activation of the spacecraft and instruments followed. The moment that the ACIS Team was waiting for occurred on August 12th, when the ACIS door was finally opened without a hitch. Fig. 10 shows the relief of the some of the team members.

[1] http://www.nasa.gov/mission_pages/shuttle/shuttlemission/archives/sts-93.html

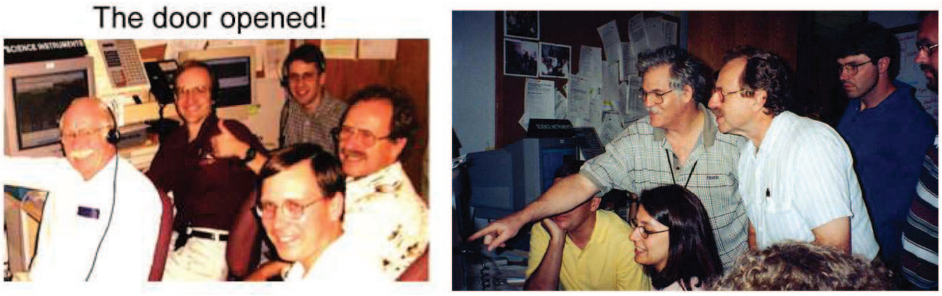

Figure 10. Left: The ACIS team feeling much relief now that the ACIS door was open including yours truly (Courtesy of Mark Bautz, MIT); right: The Project Scientist, Martin Weisskopf, pointing and the ACIS PI, Gordon Garmire, watching the data from Leon X-1 being acquired as the first image of an X-ray source viewed by the Chandra X-ray Observatory (http://chandra.harvard.edu/graphics/resources/illustrations/occ/group/group7-721.jpg).

The next step was to verify that the telescope was working and focusing X-rays. After suitable guide stars were located, Chandra began to accumulate data on the ACIS camera back illuminated CCD. After a few tense moments an image began to appear, somewhat off-axis but in reasonably good focus. The telescope scientist, Leon van Speybroeck, breathed a huge sigh of relief at this point and said in his low-key manner, “At least we don’t have a pile of glass at the bottom of the telescope tube!” The project scientist and the ACIS PI are shown in Fig. 10 watching the data come in on the source we called Leon X-1 in honour of the Telescope Scientist.

8. Results

Next I would like to show just a few images from the past ten years of observations. The Observatory and instruments have performed essentially flawlessly for this time span. There was a brief period at the very beginning of the mission when ACIS was exposed to protons from the trapped radiation belts that were scattered by the telescope onto the CCDs. This caused radiation damage to the front illuminated CCDs, reducing their ability to transfer charge, but by placing ACIS out of the telescope focal plane during the radiation passages, further damage could be avoided. The back illuminated CCDs are protected by 40 microns of silicon before the protons could reach the transfer portion of the CCD. This was enough shielding to prevent damage to these devices. Data analysis techniques have been developed by the ACIS team to partially mitigate this problem in the front illuminated CCDs (Townsley et al. 2000).

The closest massive black hole is the one at the Galactic Centre associated with the radio source Sgr A*. This object is found to emit X-rays, but at a very low level of about 2×10^{33} erg/s, which is some nine orders of magnitude below typical AGN activity (see Fig. 1). This may be the result of a supernova remnant that has engulfed the black hole and its environs, thereby making accretion difficult (see Maeda et al. 2002). The X-ray source has been observed to flare on a daily basis, increasing in intensity by nearly two orders of magnitude for a period of order an hour, then

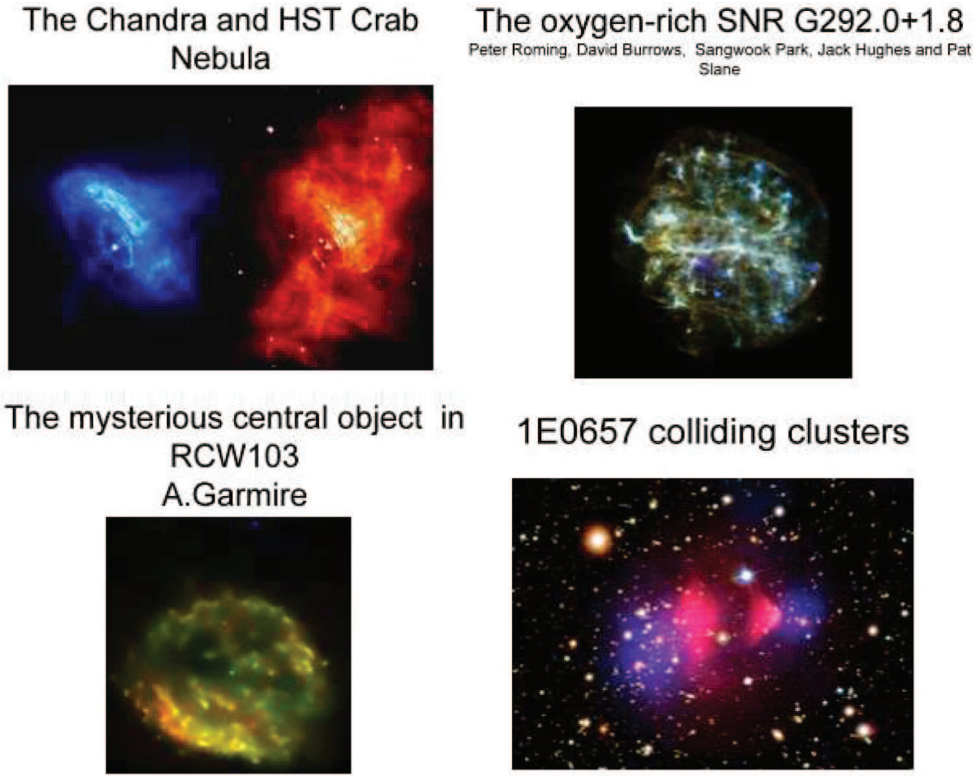

Figure 11. Upper left: The Crab Nebula as viewed by Chandra (left) and Hubble (right); (Courtesy of David Burrows, Penn State); upper right: the oxygen-rich SNR G292.0+1.8. The pulsar is located just south of the central bar in the blue nebulosity (courtesy of Peter Roming, Penn State); lower left: The supernova remnant RCW 103 with a central pulsar of extremely slow rotation period of 6.67 hr (courtesy of Audrey Garmire, Penn State); lower right: the colliding clusters of galaxies, 1E0657 (http://chandra.harvard.edu/photo/1e0657/1e0657.jpg).

falling rapidly back to its quiescent level (Baganoff et al. 2001). The cause of the flares is not known. I'm sure Chandra would have been interested in this phenomenon.

Another object that exhibits relativistic plasma phenomenon is the Crab Nebula (Fig. 11). In a time laps image of the Crab Nebula, some of the wisps are seen to move at velocities as high as 0.5c (Hester 2008). The pulsar is clearly the centre of the wisp activity.

Another supernova remnant containing a pulsar is G292.0 +1.8. This is one of the few oxygen rich remnants in a nearby galaxy and shows clumps of gas rich in Mg, Si and S (Park et al. 2007). A strong shock front can be seen along some of the outer perimeter of the remnant. The pulsar is in the blue nebulosity to the southwest portion of the nebula in Fig. 11 (upper right).

Another supernova remnant, RCW 103, is shown in Fig. 11 (lower left). This remnant was the first SNR with a pulsar located at the very centre of the nearly circular nebula (Tuohy & Garmire 1981). The pulsar has been found to be the slowest rotating neutron star with a period of 6.67 hr (De Luca et al. 2006). It is likely to be in a binary system with the same period (Pizzolato et al. 2008) or a magnetar with a fall-back disk (Li 2007). This pulsar experienced a large outburst in 2000, increasing in luminosity by a factor of 100, then decaying very slowly over the next seven years (Garmire et al. 2000). No optical or IR candidate has conclusively been found for this object (De Luca et al. 2008).

The last object I wish to show is the colliding clusters of galaxies 1E0657 (Fig. 11, lower right panel). This remarkable collision reveals that the dark matter (which does not interact with baryons and is traced by gravitational lensing) follows the galaxies through the collision process (the blue clouds), while the hot plasma shows strong interaction (pink clouds). This collision has been used as strong evidence for the presence of dark matter in the clusters as opposed to modified gravity to explain the velocity dispersion of galaxies and the confinement of the hot plasma found in clusters of galaxies (Clowe et al. 2006).

The naming of the Chandra X-ray Observatory was the result of a contest conducted by NASA and open to the world. There were more than 6000 entries from 61 countries. The winners were a high school student form Idaho, Tyrel Johnson and a high school teacher from California, Jatila van der Veen. These two submitted the winning essays that selected Chandra in honour of Subrahmanyan Chandrasekhar as the name of this 'Great Observatory'.

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I would like to thank the many, many scientists, engineers, technicians and managers who contributed to the wonderful success of this Great Observatory, the Chandra X-ray Observatory. In particular, I would like to thank Dr. Mark Bautz of the Kavli Institue for Astrophysics at MIT and Dr. Robert Burke of the Northrop Grumman Aerospace Systems group for several images which they provided. For much more detail concerning the history and development of the Observatory, the reader is referred to the books *Revealing the Universe: the making of the Chandra X-ray Observatory* by W. and K. Tucker, and *Secrets of the Hoary Deep* by R. Giacconi.

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