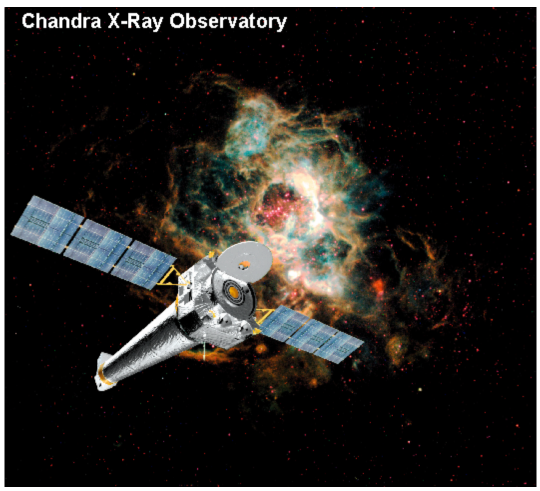
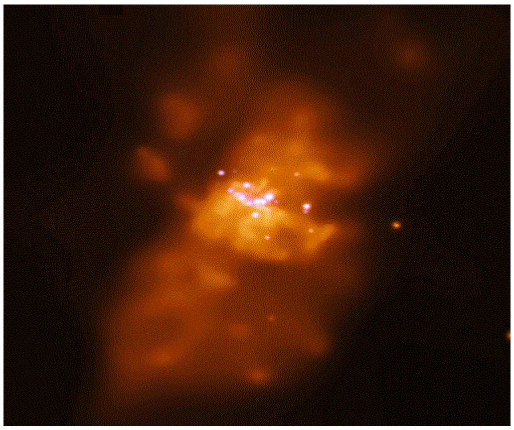
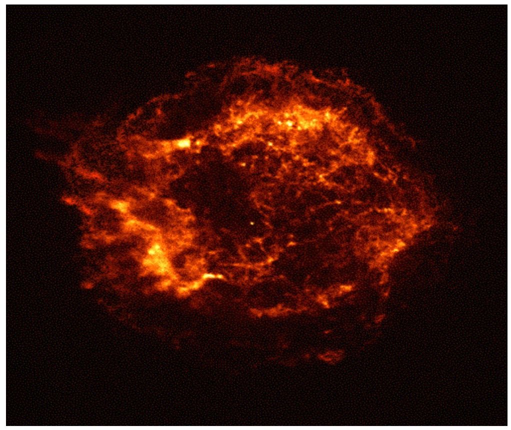
Chandra X-ray Observatory



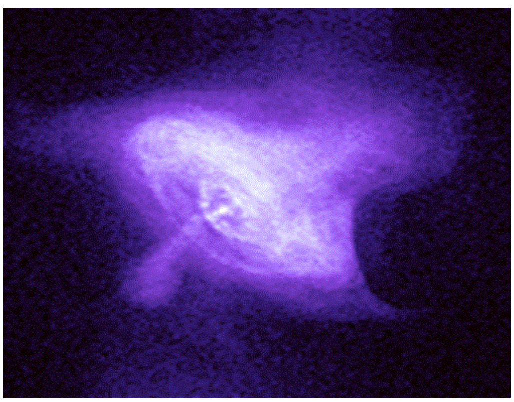
Chandra X-ray Observatory



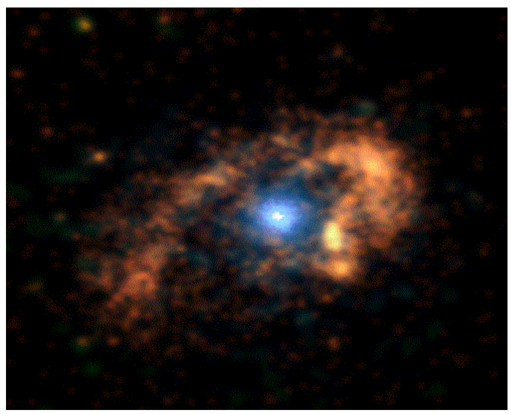
M82 Galaxy



Cassiopeia A



Crab Nebula



Eta Carinae

Chandra X-ray Observatory

- **CXO Overview**
- **Chandra History**
- **Challenges**

1. Mirrors

2. Restructuring

3. Science Instruments

4. Integrated Testing

5. Management

6. HRMA Alignment

7. Cleanliness

8. SIM Mechanisms

9. X-ray Calibration Facility

10. On-orbit Proton Radiation

Chandra X-ray Observatory: Overview

- **ONE OF THE 4 "GREAT OBSERVATORIES"**

- **PROGRAM OBJECTIVE:** The objective of the Chandra Program is to Make Fundamental Scientific Discoveries and Contribute to our Understanding of the Universe Through Rigorous Analysis and Distribution of Unique Scientific Data. This responds to the the NASA Strategic Plan in the Space Science Enterprise by responding to the mission, "To advance and communicate scientific knowledge and understanding of Earth, the Solar System, and the Universe."

- **SCIENCE OBJECTIVES:**
  a. Determine the nature of celestial objects from stars to quasars
  b. Understand the nature of physical processes which take place in and between astronomical objects
  c. Understand the history and evolution of the universe

- **PRINCIPAL CUSTOMERS:**
  Astronomical Science Community
  NASA Headquarters, Office of Space Science (OSS)
  Congress and the General Public

Chandra X-ray Observatory: Overview

o KEY SCIENCE PERFORMANCE REQUIREMENTS:

- Percent Encircled Energy (How sharp is the image?)
- Registration (Where is the target in the sky?)
- Effective area (How many photons can you collect?)

o KEY DERIVED REQUIREMENTS FROM PERFORMANCE REQUIREMENTS:

- Mirror size and design
- Focal length
- Pointing
- Thermal stability
- Instrument sensitivity
- Fiducial Transfer System

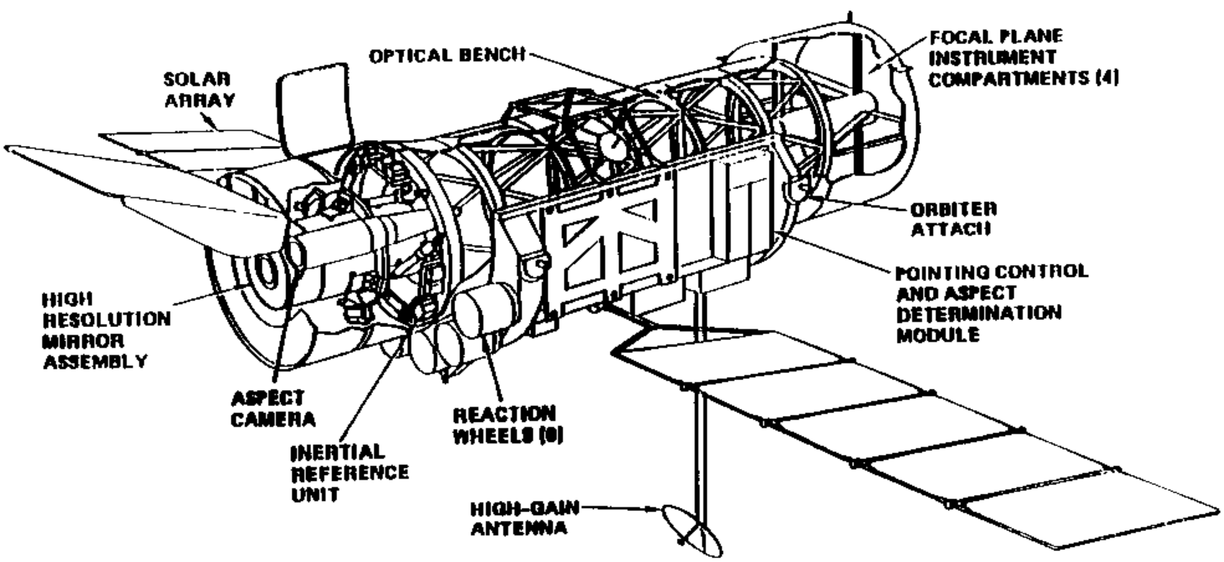
o NEXT, FILL IN THE REST OF THE REQUIREMENTS

o ONCE REQUIREMENTS ARE SET, CONCEPTS CAN BE DEFINED AND THE DESIGN CAN BE DEVELOPED

Chandra X-ray Observatory: Overview

BASELINE AXAF CONFIGURATION

A PRELIMINARY DESIGN!

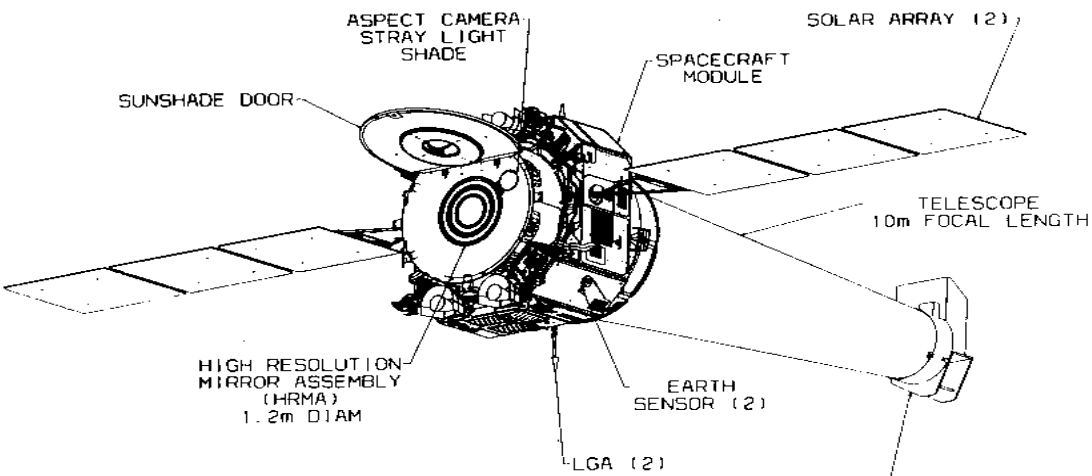


KEY FEATURES

55 FT LONG	600 km ORBIT
65 FT WINGSPAN	SHUTTLE LAUNCH
32,800 lbs LAUNCH WT	6 MIRROR PAIRS
ORBITAL SERVICING	10 M FOCAL LENGTH

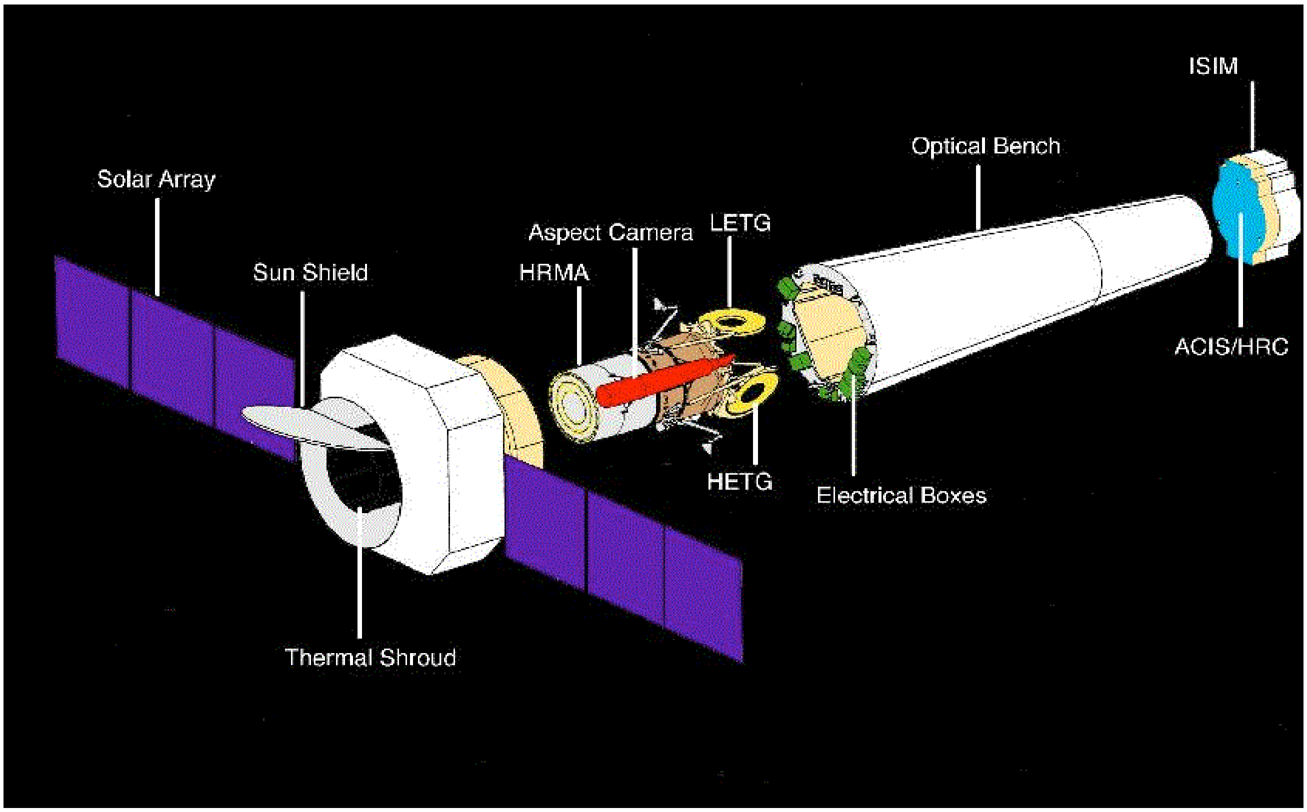
Chandra X-ray Observatory: Overview

NOTE THE FINAL DESIGN!

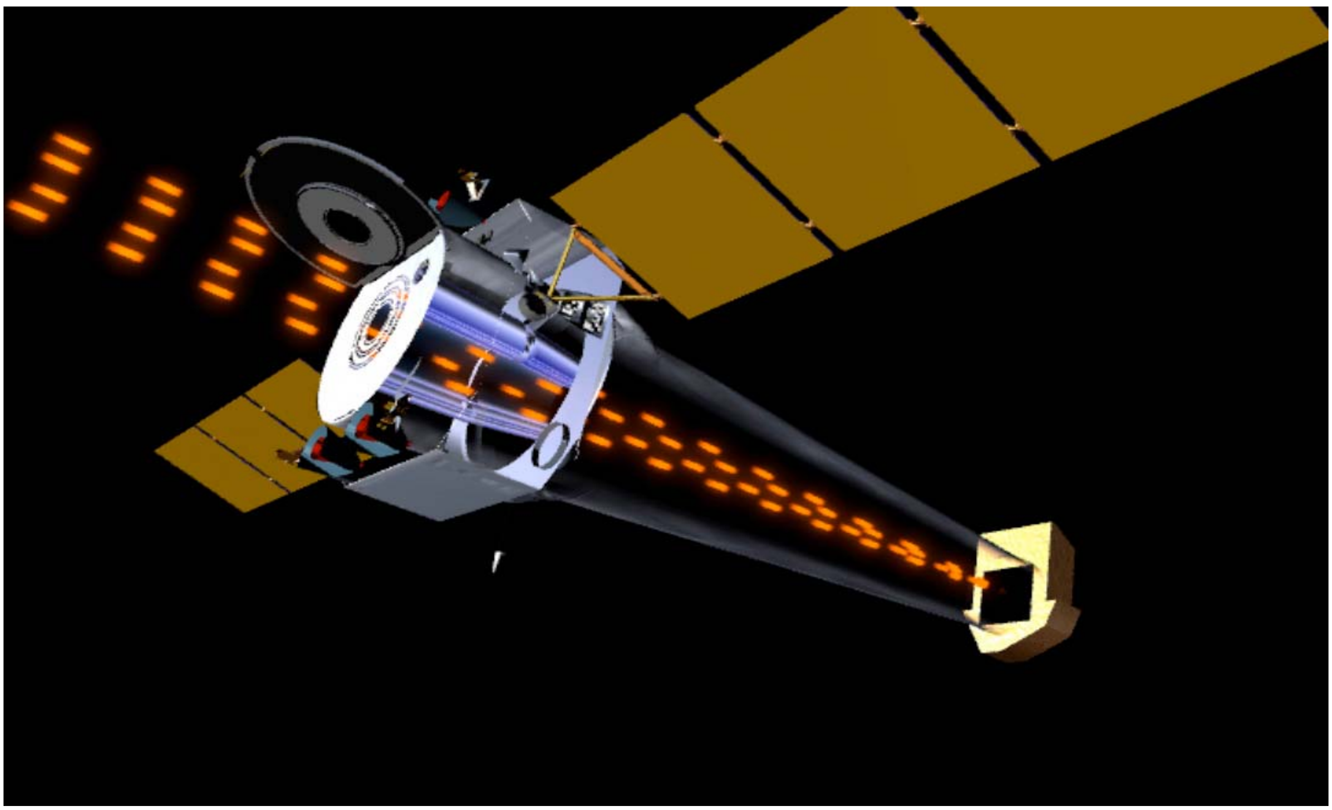


WING SPAN:	64	FT
LENGTH (DOOR CLOSED):	38.7	FT
LENGTH (DOOR OPEN):	45.3	FT
LAUNCH WEIGHT:	12,930	LB
ON-ORBIT WEIGHT:	10,560	LB (10,050 BASIC)
EOL LOAD POWER:	2,366	W

Chandra X-ray Observatory: Overview



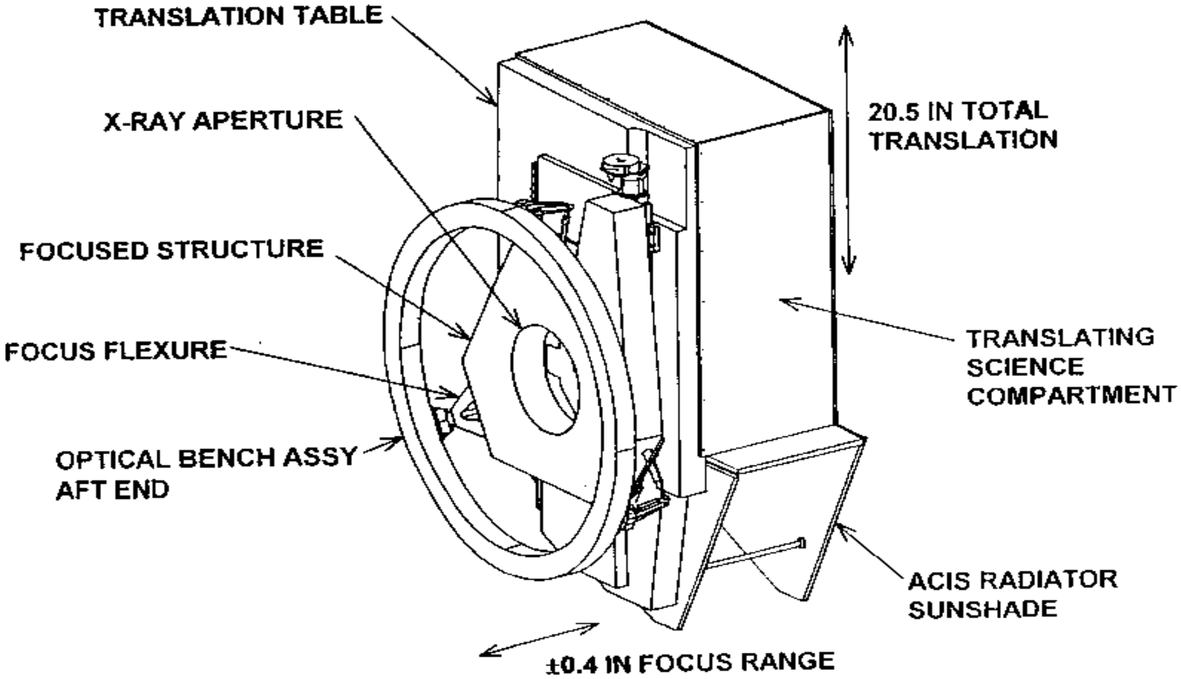
Chandra X-ray Observatory: Overview



Chandra X-ray Observatory: Overview

o AXAF Mission Definition Study	**1978**
o HQ approval for new start:	1988
o Authority to Proceed (ATP) for Prime contract:	January 1989
o ATP for Science Instruments:	June 1990
o Mirror validation test (VETA-1):	June 1991
o Program Restructure:	1992
o System Requirements Review:	December 1992
o Preliminary Design Review:	November 1994
o Critical Design Review:	February 1996
o Mirror delivery to Calibration Facility:	November 1996
o Shipped to KSC:	February 1999
o Launched:	**July 23, 1999**
o Orbit:	10,000 km x 140,000 km at 28.5° inclination
o Final Orbit Achieved:	August 7, 1999
o Sunshade Door Opened:	August 12, 1999
o First Safemode (ground error):	August 17, 1999
o End of Orbital Checkout:	September 19, 1999
o End of First Eclipse Season:	October 12, 1999

Chandra X-ray Observatory: Overview

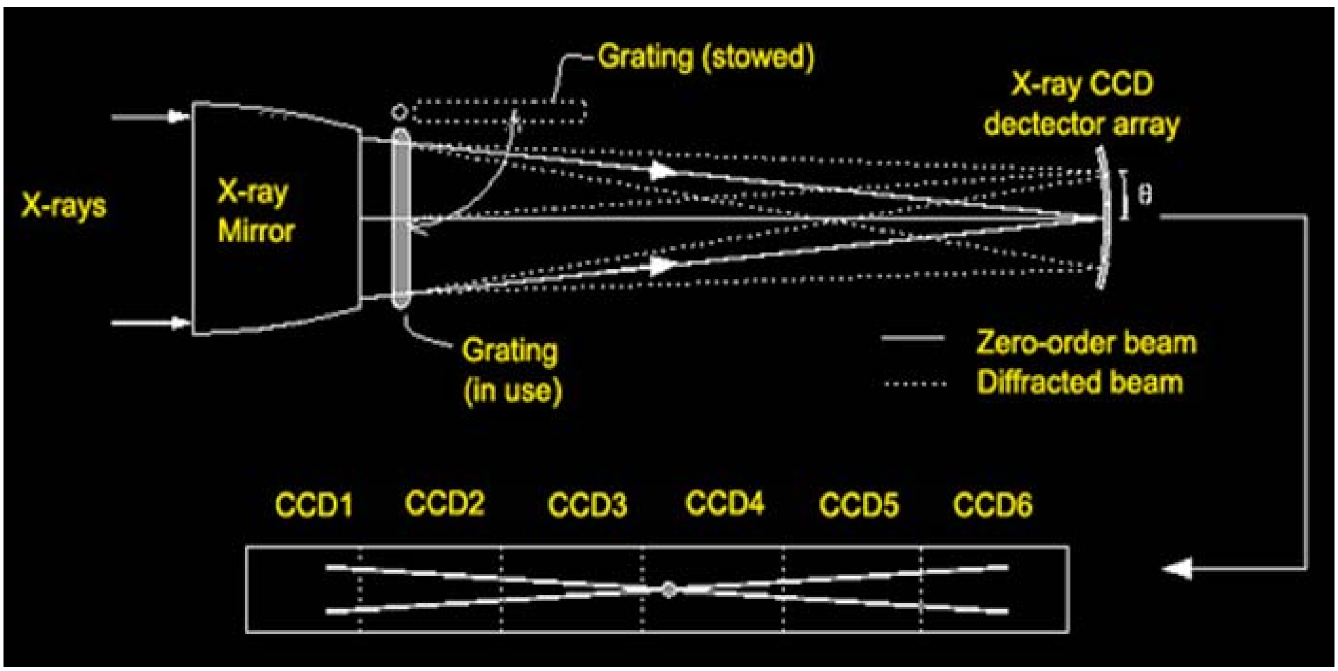


Chandra X-ray Observatory: Overview

Science Instruments	Principle Investigator	Instrument Description
Advanced CCD Imaging Spectrometer (ACIS)	Gordon P. Garmire Penn State	Array of 10 CCD devices with Sub-arcsecond angular resolution
High Resolution Camera (HRC)	Steven S. Murray SAO	Micro-channel plate imager with better than 0.5 arcsecond angular resolution
High Energy Transmission Grating (HETG) (includes both high and medium energy gratings	Claude R. Canizares MIT	Spectral BW from 0.4 to 8.0 keV; Resolution = 800 at 1.0 keV; ACIS images spectral dispersion of gratings
Low Energy Transmission Grating (LETG)	Albert Brinkman SRU, Utrecht, Netherlands	Spectral BW from 0.1 - 3.0 keV; Resolution = 750 at low energies; HRC images spectral dispersion of grating

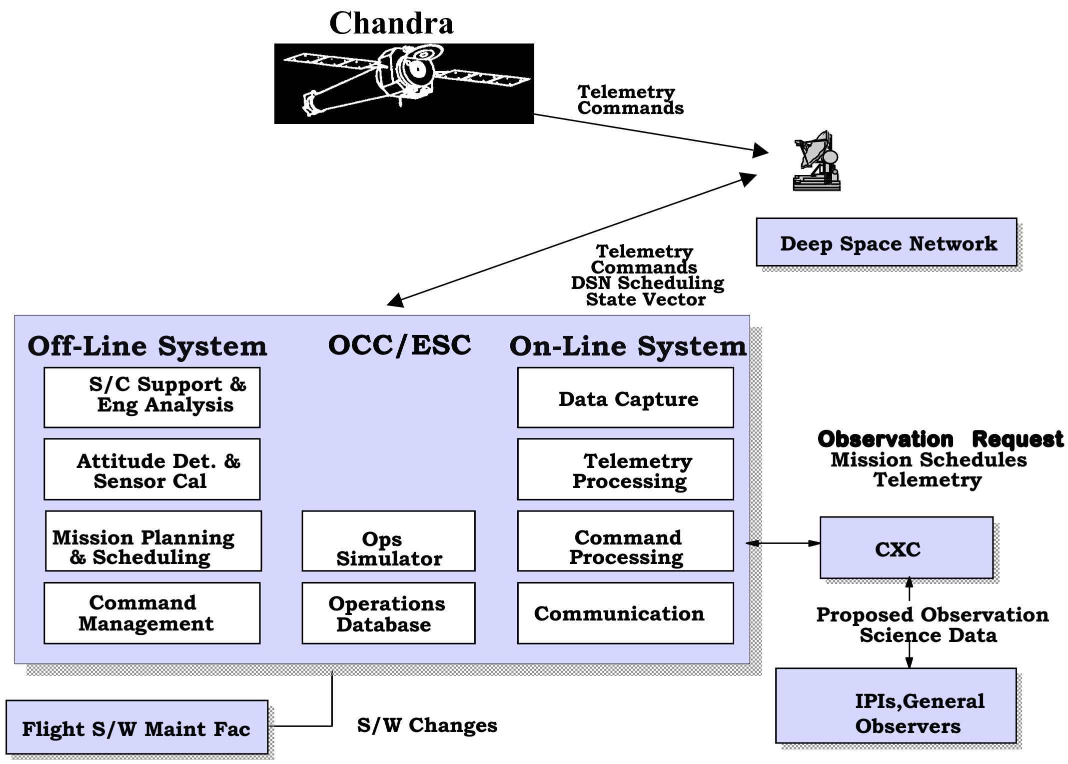
Chandra X-ray Observatory: Overview

Chandra X-ray Observatory: Overview



Chandra X-ray Observatory: Overview

Chandra Ground System Architecture



Chandra X-ray Observatory: History

o **AXAF MISSION DEFINITION STUDY BEGAN IN 1978.**
- Based upon successful HEAO series
- Extrapolated results and new technology improvements to derive top level performance.
- Maintained a "study" level of effort for several years.
- In order to "sell" concept, elected early on to involve independent (non-profit) party, SAO, to review all telescope studies and work
- Also brought on-board a senior telescope scientist and various interdisciplinary scientists in 1985.

o **TRW WAS SELECTED AS PRIME CONTRACTOR IN 1988**

o **AXAF WAS GIVEN A NEW START IN 1989.**
- Full new start authority was contingent upon successful completion of mirror technology test
- Test mandated by congress in 1991 and completed successfully and on-time.
- NASA HQ approved for a new start with metrics along the way

Chandra X-ray Observatory: History

- **TO REDUCE LIFE CYCLE COST, PROGRAM RESTRUCTURED IN 1992**
  - Imaging mission
    - Reduced mirror pairs from 6 to 4
    - Dropped 2 focal plane instruments (now only 2, plus 2 gratings)
    - Dropped servicing requirement
    - Changed lifetime from 15 years to 5 years
    - Placed into higher orbit to increase observing time and preserve science objectives
  - Spectroscopy mission
    - Took one of the instruments and built a mission around it
    - To save cost, this was to be built totally in-house at MSFC

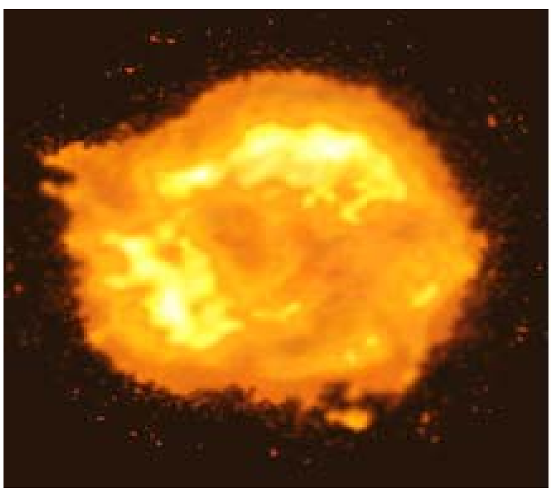
- **NATIONAL ACAEDMY OF SCIENCES ENDORSED PROGRAM**

- **AXAF-SPECTROSCOPY MISSION WAS CANCELLED BY SENATE IN 1994**
  - Program was on track and within cost (?!)
  - Smaller version of the instrument slated for the Japanese mission ASTRO-E
  - ASTRO-E mission was lost during ascent earlier this year.

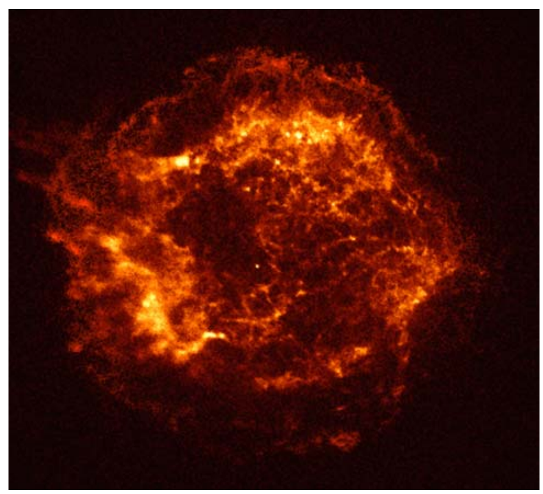
Chandra X-ray Observatory: Challenges

Why is imaging so important?

Imaging allows scientists to pinpoint where in space the x-rays are coming from. The more precision the telescope has, the better the resolution to identify the X-rays. This allows even further detail and scientific discovery in understanding more about the object and how it came to be.



Rosat Image



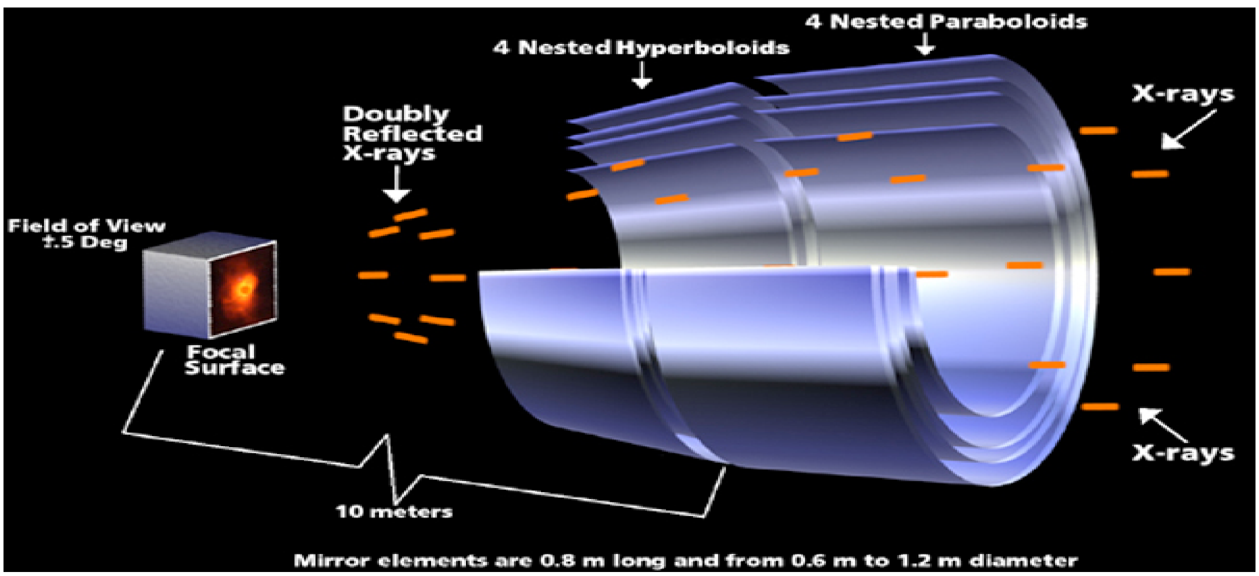
Chandra Image

Chandra X-ray Observatory: Challenges

1. **Mirrors (TECHNICAL)**
   - o **BIGGESST CHALLENGE WAS MIRROR DEVELOPMENT**
     - Mirrors had never been figured to this precision for this size
     - Program needed to develop innovative approach to mirror fabrication and testing
   - o **SUBSCALE STRATEGY**
     - Develop single mirror pair comparable to smallest Chandra (AXAF) mirror pair
     - Demonstrate technology to build mirrors
     - Develop in-process metrology, feed metrology data into computer modeling, predict resulting mirror performance, and validate with newly-developed optical test methods
     - Program developed Technology Mirror Assembly (TMA)
     - Program selected/developed 3 types of metrology measurements
     - All measurements were fed into analytical software programs to predict performance.
     - Predicted performance was compared to actual performance of mirrors.
       - o The initial performance did not quite match predictions.
       - o A small gap was found between the 3 types of metrology metrics that left some part of mirror surface undefined.
       - o Metrology was enhanced; mirror flaw was found; mirror was re-polished.

Chandra X-ray Observatory: Challenges

High Resolution Mirror Assembly (HRMA)



Chandra X-ray Observatory: Challenges

What makes Chandra Unique?

Chandra has outstanding imaging precision; its mirrors are the largest, the most perfectly aligned, and smoothest ever built. The images Chandra makes are 25 times sharper than the best previous x-ray telescope.

Polishing a CXO Mirror Shell

CXO hrma assembly

Chandra X-ray Observatory: Challenges

1. **Mirrors (TECHNICAL)**
   - **IN-PROCESS METROLOGY MEASUREMENTS AND CROSS-CHECKS**
     - 4 independent metrology measurements on mirrors
     - Each has overlapping frequencies so that cross-checks with one or more of the other metrology devices is performed.
     - Each metrology measurement device was improved over the TMA devices.
     - The testing of the metrology devices was extensive.
     - During the mirror assembly, a co-located team of Government and contractor personnel reviewed all of the metrology data as it was taken.

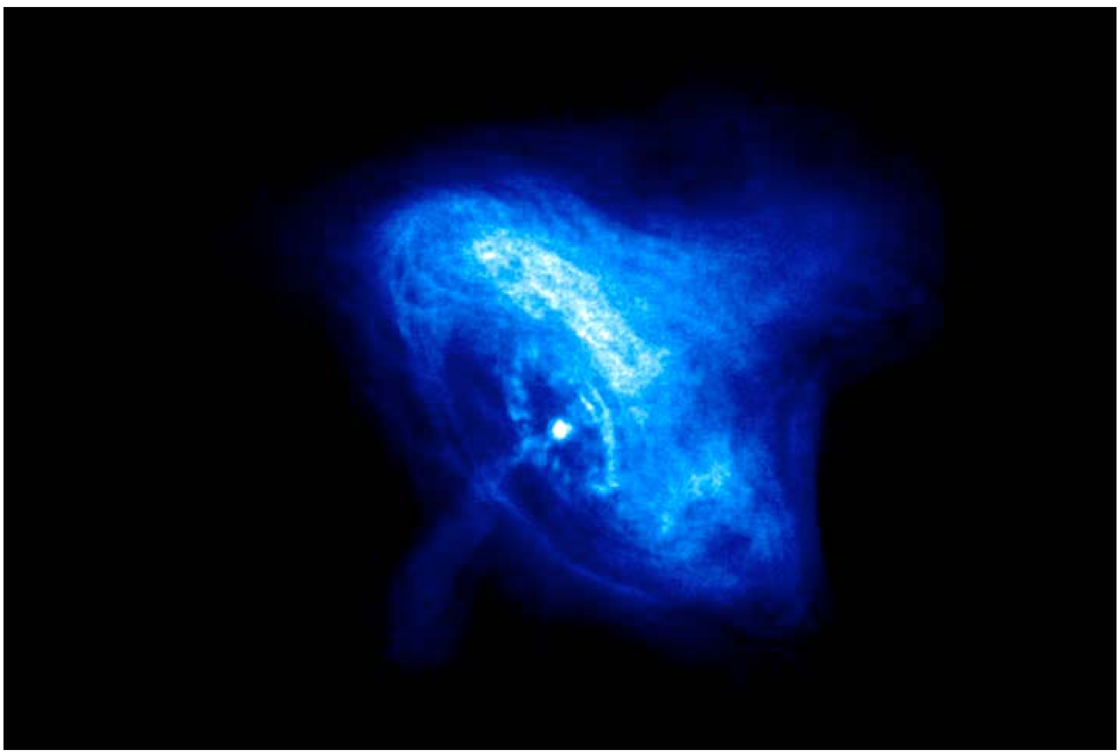
   - **EARLY TESTING OF LARGEST MIRROR PAIR MANDATED BY CONGRESS**
     - H1/P1 tested in a VETA-1 (Verification Test Article) configuration at MSFC's XRCF
     - Testing was performed on-time and showed performance better than mandated spec value.
     - A second development test, VETA-2, took outer mirror pair and assembled them into a flight High Resolution Mirror Assembly (HRMA) using nominal procedures and Ground Support Equipment (GSE)
       - This HRMA (with mass simulators for remaining shells) was shaken as a structural test article to verify alignment stability

Chandra X-ray Observatory: Challenges

1. **Mirrors (TECHNICAL)**
   - o **END-TO-END X-RAY TESTING OF FINAL HRMA ARTICLE**
     - Performed at XRCF under direction of MSFC
     - Used flight science instruments and HRMA
     - Demonstrated quality mirrors and compared well with predictions
   - o **KEY TO SUCCESS IS GOOD SYSTEMS ENGINEERING**
     - Necessary because of multiple separate parties, academia, non-profits, and foreign groups
     - **LESSON LEARNED**: Perform multiple cross-checks wherever possible
     - **LESSON LEARNED**: Let more than one group perform review
     - **LESSON LEARNED**: No substitute for direct test or measurement
     - **LESSON LEARNED**: Keep science informed and part of the decision-making process
     - **LESSON LEARNED**: Establish error budgets and allocate error terms early on, and continually review them

Chandra X-ray Observatory: Challenges

1. **Mirrors (TECHNICAL)** **PAYOFF!**



Chandra X-ray Observatory: Challenges

2. Descope (PROGRAMMATIC)

o NEXT BIGGEST CHALLENGE WAS COST – NASA HQ & CONGRESS DID NOT WANT TO PAY THE INITIAL PRICE

- Total recurring cost was problem
- Solution: Remove servicing and reduce life from 15 yrs to 5 yrs.
- 2 instruments were dropped as well
- Also, Systems Engineering was cut!

o MITIGATION

- Finally settled on moving Chandra to a higher orbit to minimize earth eclipse but it needed to be high enough to avoid disturbance from Van Allen radiation belts.
- To go higher in orbit, Chandra had to lose weight so that an upper stage could achieve the higher orbit.
- Also studied new launch vehicles to achieve the best efficiency for the available funds.
- Keep the Shuttle launch vehicle.
- Weight needed to drop more than a factor of 2!

Challenges

2. Descope (PROGRAMMATIC)

o WEIGHT REDUCTION

- Use new technology lightweight composites for telescope.
- MSFC had never used this percentage of composites for a large space structure
- Since the mirrors were a significant weight contributor, 2 mirror pairs were dropped.
- SIM was changed to all composite structure.

o WEIGHT REDUCTION IMPACTS

- Developed new methods of analyzing total structure
- Since composites crack, adopted a new handling paradigm to prevent damage
- Developed new methods of structurally testing composite integrity
- Since SI's were cantilevered out in Shuttle cargo bay, weight problem remained acute for SI's and SIM until late in program
- SIM and SI's weight containment policy resulted in constant attention and change and ate most of program slack
- Universities had different structural analysis tools than contractors, so communication and common understanding was difficult at times.

Chandra X-ray Observatory: Challenges

2. Descope (PROGRAMMATIC)

o MANAGEMENT TECHNICAL, ENGINEERING, AND PROGRAMMATIC OVERSIGHT

- Set element weight allocations.
- Define frequent reporting scheme; address frequently.
- Understand and penetrate the tradeoffs of weight loss
- Balance need for adherence to schedule versus time to fix/complete mandatory events
- Revise allocations as needed to get the job done.
- Keep all elements informed of progress.
- Keep communication flowing!
- Be sensitive to the impact of changes to all areas not just the ones directly affected by a change.

o COMPENSATE FOR CONTRACTOR LOSS OF SYSTEMS ENGINEERING EFFORT

- Established Technical Oversight Panels
- Controlled the external ICD's and led the ICD working groups
- Perform all top-level (Level II) systems engineering activities
- Establish technical presence at locations where the action is.

Chandra X-ray Observatory: Challenges

2. Descope (PROGRAMMATIC)

- **o** **<u>LESSONS LEARNED</u>**:
  - Set resource allocations early and continue to monitor, tradeoff, and refine them through to delivery
  - Maintain strong Systems Engineering group throughout program
  - Maintain controlled schedule and carefully evaluate any changes to schedule.
  - Set up routine to have periodic meetings will all elements, the more hectic the phase the more critical the need.
  - At least during critical times, plan and schedule on-site representation

Chandra X-ray Observatory: Challenges

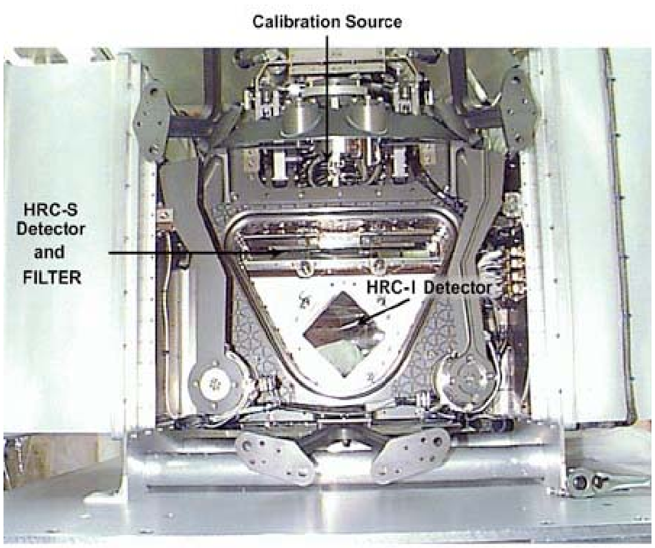
Hard work pays off!

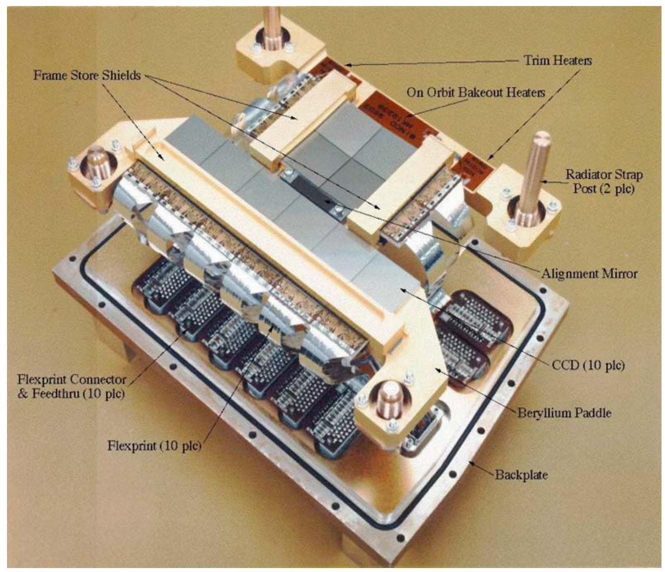
Chandra X-ray Observatory: Challenges

3. Science Instruments (TECHNICAL)

- **ACIS NEW TECHNOLOGY ITEMS**
  - ACIS used 1024 x 1024 pixel CCD's, larger than anything made like it.
  - ACIS also cooled the CCD's to -120C for the first time
  - A new type of X-ray CCD was developed for 2 of the 10 CCD's
  - Very low noise signal chain
  - Unique application of paraffin actuators for door mechanism

- **NEW TECHNOLOGY PROBLEMS**
  - Radiation susceptibility
  - Thermal extremes for flexible multilayer circuit cards
  - Low yields for the new type of CCD's
  - ESD sensitivity
  - Extensive software development
  - Complicated and sensitive procedures
  - ACIS sunshade temperature extremes





HRC Detector

ACIS Detector

Chandra X-ray Observatory: Challenges

3. Science Instruments (TECHNICAL)

o HRC NEW TECHNOLOGY ITEMS

- Low noise signal chain (different concept than ACIS)
- 3 Microchannel plates linked together
- Accurate event timing

o NEW TECHNOLOGY PROBLEMS

- Spacecraft charging protection
- Spurious noise susceptibility

o BOTH GRATINGS DEVELOPED NEW METHODS OF DEPOSITING FINE MESH STRUCTURES ON THIN FILMS

- Unknown is vibration sensitivity
- Much work done early on to verify adequacy

3. Science Instruments (TECHNICAL)

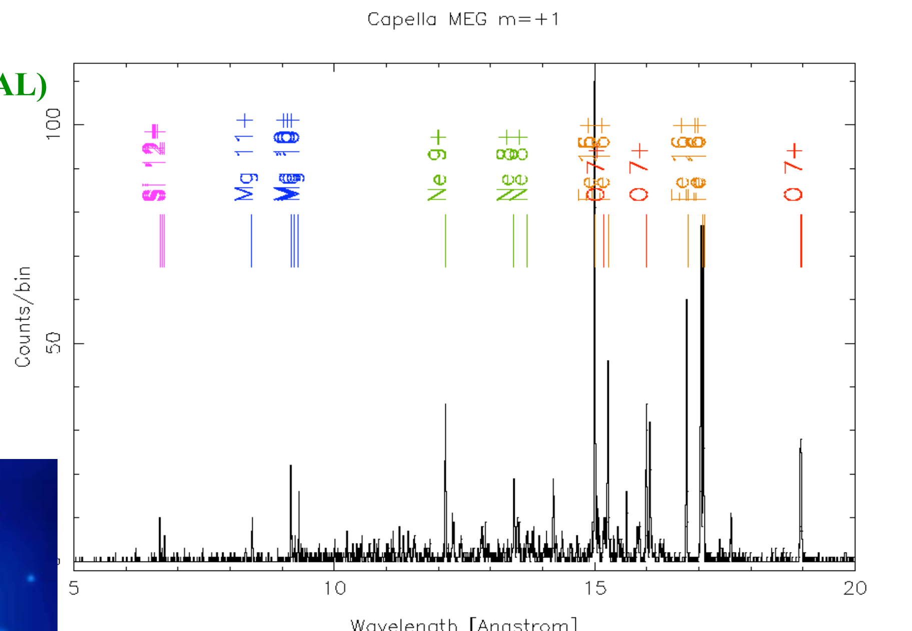
- **GOOD SYSTEMS ENGINEERING AND SOUND COMMUNICATIONS**
  - Ensure participation in working groups
  - Keep each party informed when internal as well as interface changes occur
  - Encourage teamwork
  - Balance need for adherence to schedule versus time to fix/improve
  - Keep science involved.
  - Bring in discipline experts when needed (don't be afraid to go outside of the program)

- **LESSONS LEARNED**:
  - Maintain awareness of SI's at the same level as other flight hardware.
  - Establish standing Interface Working Groups with mandatory SI participation
  - Keep science involved in engineering activities.
  - When problems occur, go outside of MSFC to get help when value-added.
  - Encourage teamwork. Many times, programs suffer culture clash between SI's and prime contractors.

Chandra X-ray Observatory: Challenges

3. Science Instruments (TECHNICAL)

- **PAYOFF:**



Chandra X-ray Observatory: Challenges

4. Integrated Testing (ENGINEERING)

- **INTEGRATION IS ALWAYS A CHALLENGE**
  - Each group has a different test paradigm
  - Communication inherently tougher from group to group
  - Each group brings its own GSE, which is more often than not incompatible with the other groups' hardware and software.
  - Logistics of who does what when must be carefully choreographed
  - Schedules and expectations are always optimistic and success-oriented

- **CHALLENGE MET!**
  - Created a working group to address integration both at Ball for the ISIM and later at TRW
  - Documented the integration and test planning in an ad hoc document
  - Good working relationship focused on teamwork and getting the job done
  - ISIM integration and testing went OK, but did have surprises that took some time to fix.

Chandra X-ray Observatory: Challenges

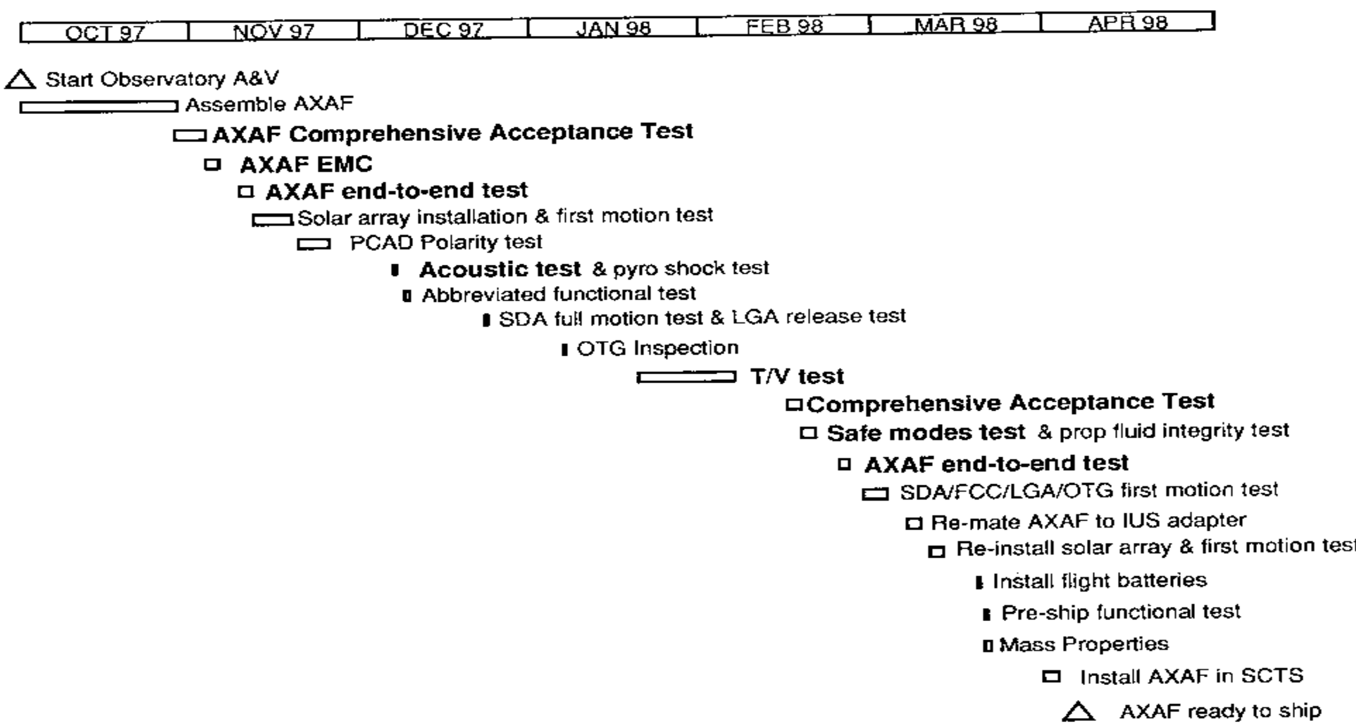
4. Integrated Testing (ENGINEERING)

- **EVEN THE BEST LAID PLANS……**
  - During Observatory integration, TRW couldn't hold schedule
  - Problem caused by antiquated EGSE and software
  - Exacerbated by unique test-only database
  - Funds to monitor activity and help out via systems engineering were cut during restructuring
  - Government did not pay enough attention and did not have a full-time Integration and Test lead.
  - Contractor chose a complicated software test script test methodology

- **RECOVERY**
  - Program Office initiated daily focus on schedule
  - Around-the-clock operations at the test site
  - New I&T Lead at TRW
  - More involvement of the MSFC technical Teams
  - MSFC technical presence to help out (not just critique) at the test site

Chandra X-ray Observatory: Challenges

AXAF Integration Flow at TRW



Chandra X-ray Observatory: Challenges

4. **Integrated Testing (ENGINEERING)**
   - **WARNING: WHEN PRESSED FOR TIME, DON'T CUT CORNERS!**
     - Reviewed all testing and did not delete any testing that was considered mandatory
     - Added systems testing to verify total system performance
     - Added some science end-to-end testing in Thermal Vacuum Test
     - Added much more end-to-end testing between the vehicle and the control center
   - **LESSONS LEARNED**:
     - Try to keep one integrated database for testing and operations
     - Define Test/Integration lead early on, before that phase begins
     - Review I&T approach including test GSE early
     - Prior to launch, perform end-to-end testing on the flight hardware from the operations center using the final version of databases and flight software
     - Encourage end-to-end testing participation of the operations group early and often.
     - If running a system level TV test, spend time to run it remotely from the operations center.
     - Give adequate time for box level testing and data system integrated testing. Don't shortcut box testing if at all possible.

Chandra X-ray Observatory: Challenges

5. **Management (PROGRAMMATIC)**
   - **CHALLENGES APLENTY**
     - Develop, build, and fly complete spacecraft
     - Multiple contracts
     - Companies, universities, foreign interests, external reviewers, other NASA centers, other government agencies
     - External budget constraints
     - Complicated new technology
   - **UNKNOWN UNKNOWNS**
     - Program restructure
     - Integration delay
     - Myriad of technical challenges
     - Changing government oversight paradigm
     - External reviews

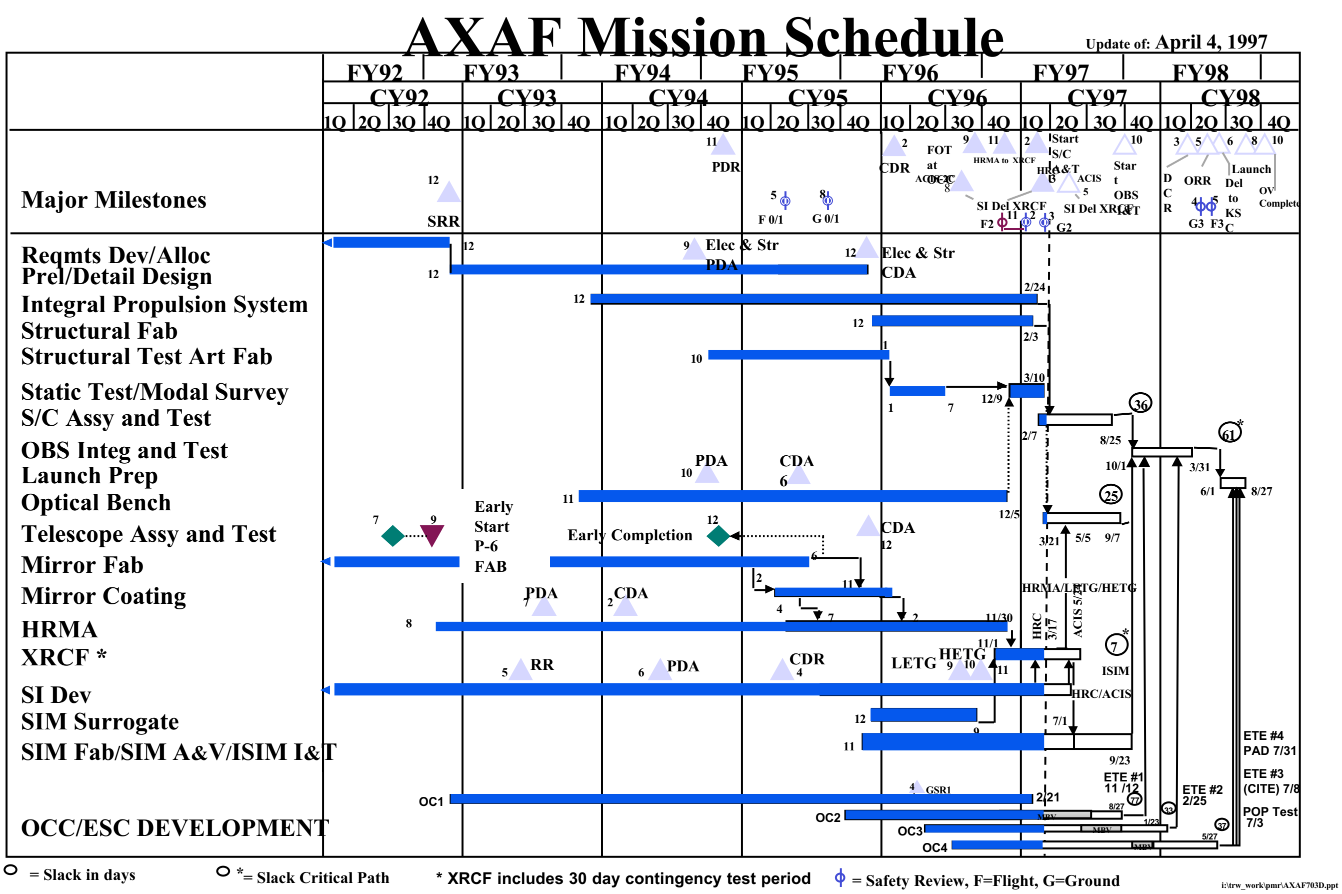
Chandra X-ray Observatory: Challenges

5. **Management (PROGRAMMATIC)**
   - **APPROACH TO SUCCESS:**
     - Experience from Hubble
     - Top management had technical background
     - Worked closely with Science community
     - Fostered teamwork, enhanced communication
     - Set up proper contracts and contract monitoring
     - Held enough reserves (until the integration activity)
     - Set MSFC technical personnel accountable
     - Good contractors with good managers
     - Solicited and received outside help when needed
     - High priority for MSFC
     - Set schedule early and balanced need for schedule adherence with need to slow down and catch our breath.

Chandra X-ray Observatory: Challenges

5. **Management (PROGRAMMATIC)**
   - **LESSONS LEARNED**:
     - Define good requirements early; get wide buy-in, hold the line against requirements creep.
     - Plan early program involvement of operations community
     - Communicate regularly with the whole team; set periodic telecons and brief issues and status.
     - Maintain strong engineering involvement early
     - Foster teamwork and assign ownership of the effort by contractors as well as CS.
     - Set up proper contracts and contract monitoring
     - Held enough reserves (at least 25%) for the amount of new technology development
     - Set MSFC technical personnel accountable to having the project elements work (not accountable to verify the contractor made it work).
     - Develop strong end-to-end systems engineering, not just the pieces
     - Solicit outside help when needed
     - If program is required to have an Independent Assessment group, get them in early and keep them in for all major reviews and resolution of all critical issues
     - Set schedule early and balanced need for schedule adherence with need to slow down and "catch our breath".

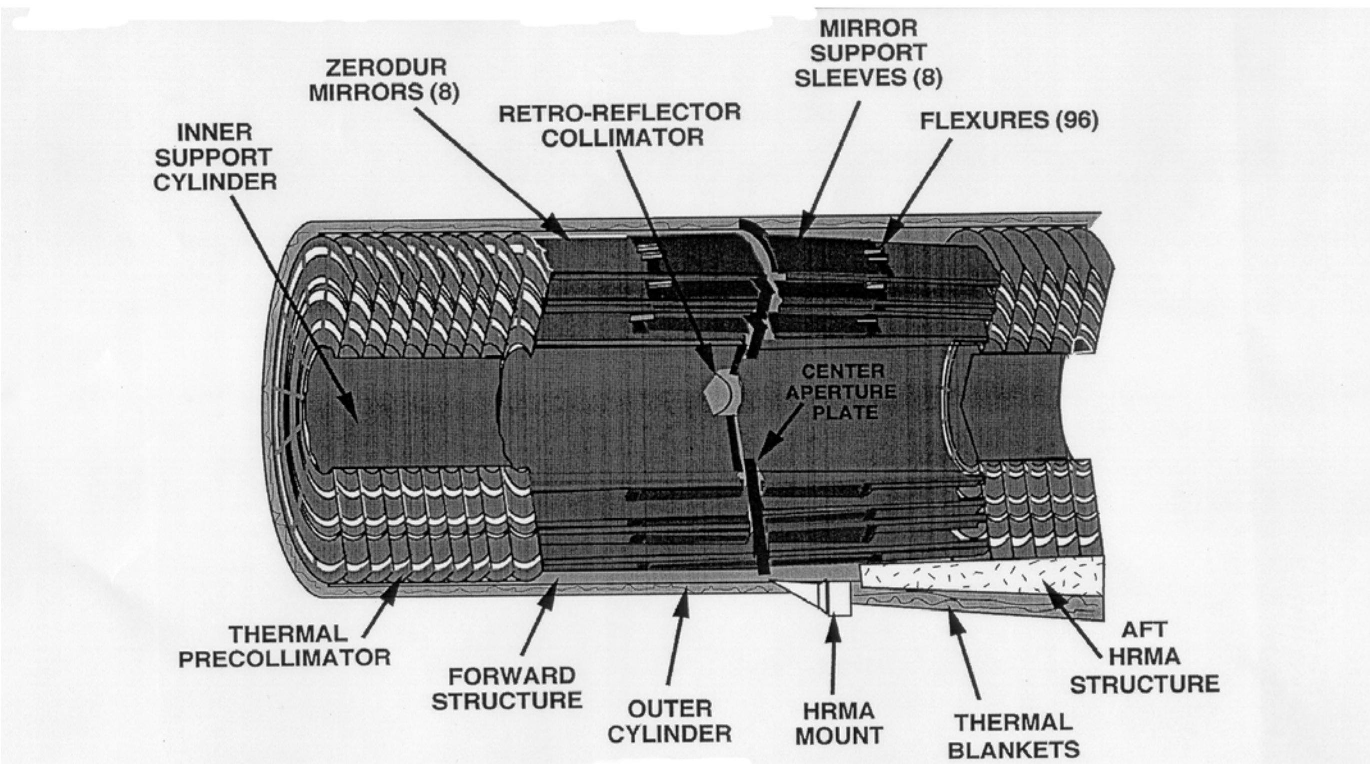
Chandra X-ray Observatory: Challenges



Chandra X-ray Observatory: Challenges

6. **HRMA Alignment and Stability (TECHNICAL)**
   - **MIRRORS MUST WORK AS A UNIT**
     - Align each mirror very accurately
     - No shell-to-shell variations
     - No bulk variations
     - No changes after XRCF calibration
     - No major changes to measured alignment of telescope after integration
   - **MIRRORS DROVE THE DESIGN**
     - Stiff, rigid structures
     - Isothermal environment
     - Critical thermal coatings
     - Thermal control very granular
     - Accurate sensors
     - Integration and test implications (how to verify)

Chandra X-ray Observatory: Overview



Chandra X-ray Observatory: Challenges

6. HRMA Alignment and Stability (TECHNICAL)

- **UNANTICIPATED PROBLEMS OCCUR! EXAMPLE: SPACECRAFT CHARGING**
  - Very tight thermal requirements for HRMA and telescope led to choice of silverized Teflon thermal blankets
  - Teflon outer surface is dielectric; it builds up charge
  - In Chandra orbit, high degree of background plasma flux charges blankets
  - Blankets eventually discharge, which can disrupt signals either radiatively or conductively
  - Major effort on Chandra to first avoid and later mitigate problem
  - SI's (being potential victims) wanted materials changed; Observatory contractor required surface for thermal reasons.
  - Thermal design won out, coupled with extensive testing and shielding of sensitive signals
  - Spark test developed to test radiative susceptibility
  - Other innovations made to reduce susceptibility, including evaluation of major Chandra-level plasma test (ultimately rejected).

Chandra X-ray Observatory: Challenges

6. **HRMA Alignment and Stability (TECHNICAL)**
   - **USE PATHFINDER**
     - Developed special alignment tower
     - VETA-2 was used as pathfinder for process
     - Kodak developed very elaborate alignment tower
     - **LESSON LEARNED**: Put effort into error budgets, allocations, and analysis
     - **LESSON LEARNED**: Get independent reviewers involved in data review
     - Final crosscheck performed at XRCF on HRMA and each shell wrt to the whole

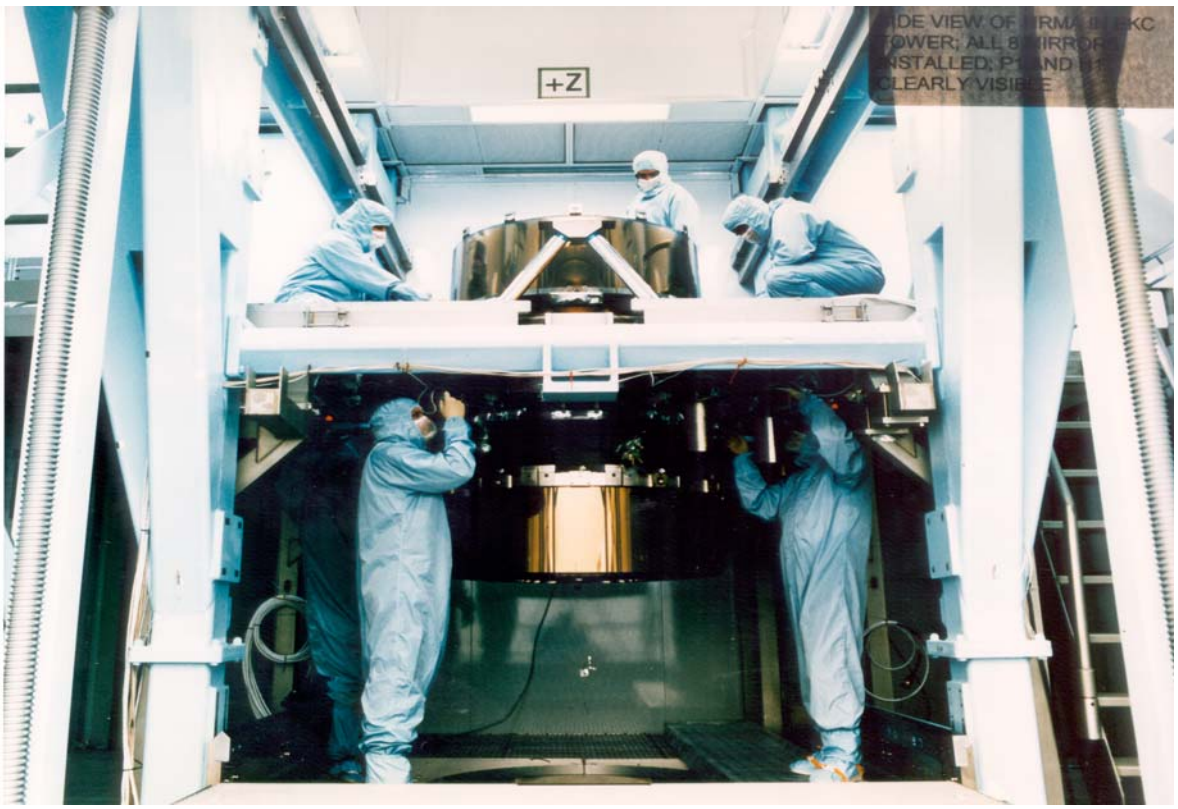
   - **PAY ATTENTION TO HRMA STABILITY**
     - Error budget allocations and accountability
     - Tested thermal stability
     - Kept Science involved
     - **LESSON LEARNED**: Multiple independent development tests and analyses prior to assembly
     - Independent review of data
     - **LESSON LEARNED**: Multiple cross-checks implemented after final assembly.
     - Developed method to check focus after Chandra environmental testing
     - Used method to check after shipment to KSC.

Chandra X-ray Observatory: Challenges

6. HRMA Alignment and Stability (TECHNICAL)

- **EXPECT UNKNOWN UNKNOWNS**
  - During mirror assembly, noted focus alignment error after the bond dried on first mirror pair
  - Problem traced to temp difference of mirror with lights on versus lights off!
  - Mirrors were set with lights on
  - Lights resulted in mirror shape change
  - Post-bond measurement made with lights off!
  - Fortunately, there was enough margin in total error allocation to press without redo
  - **<u>LESSON LEARNED</u>**: For sensitive activities, ensure consistent environment

Chandra X-ray Observatory: Challenges



Chandra X-ray Observatory: Challenges

7. Cleanliness (ENGINEERING)

o **MIRROR PERFORMANCE EXTREMELY SENSITIVE TO PARTICULATE AND MOLECULAR (FILM) CONTAMINATION**

- Much more sensitive than Hubble
- No equivalent large-scale cleanliness capability existed at MSFC

o **NEW METHODS REQUIRED**

- Better ways to measure contamination
- Improved ways of cleaning hardware
- Expanded database of allowable materials
- New paradigm had to be followed to keep everything in the optical cavity or touching it at any time clean.

o **FOCUS AREA – CONTAMINATION CONTROL**

- Science community helped push need
- Contamination budgets set early and religiously followed
- **LESSON LEARNED**: Contamination guru identified on program whose sole job was contamination
- Everything baked out to boil off contaminants

7. **Cleanliness (ENGINEERING)**
   - **AS A RULE, BAKE OUT – EXCEPTION: OPTICAL BENCH**
     - Very controversial and emotional, but bottom line was that the benefit did not outweigh schedule and cost impact
     - Tested with wipe samples and monitored outgasing constituents during TV Test
     - Cleaned very thoroughly at Kodak and witnessed by outside parties

   - **IN SPACE, CONTAMINATES COLLECT AT LOWEST TEMPERATURE – RISK: ACIS**
     - As long as mirrors stayed hotter than surrounding, little contamination would accumulate.
     - As a backup measure for ACIS, the capability to bakeout the instrument on-orbit was provided.
     - **LESSON LEARNED**: Develop backups

   - **MIRROR PERFORMANCE WOULD CHANGE (DEGRADE) IF CONTAMINATES ON SURFACE**
     - To compensate, radioactive sources were mounted in door to directly measure contamination on-orbit
     - Radioactive sources also mounted on SIM to check ACIS periodically.

Chandra X-ray Observatory: Challenges

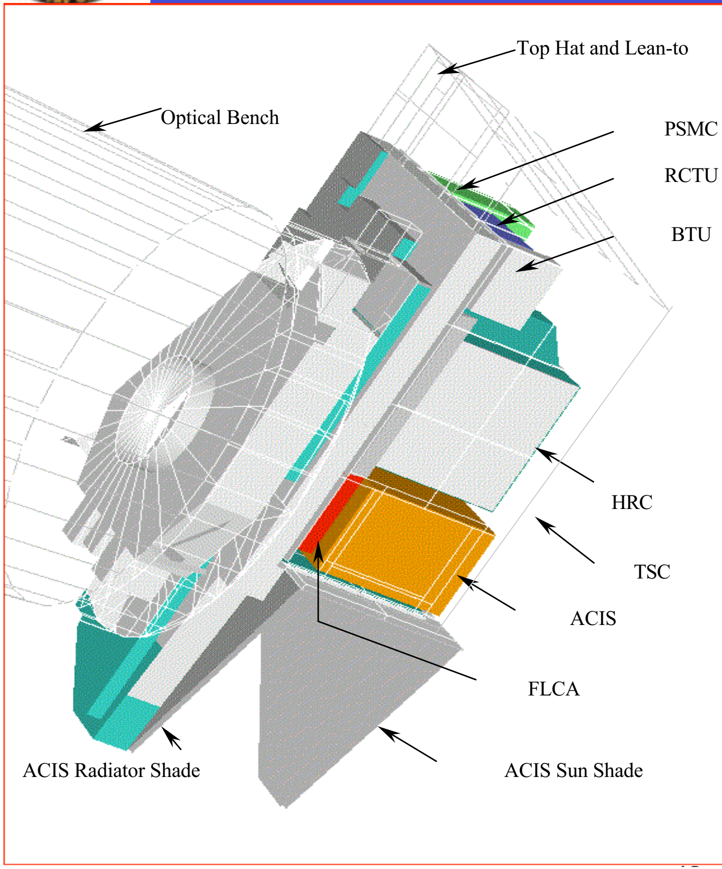
8. Science Instrument Module (SIM) Mechanisms (TECHNICAL)

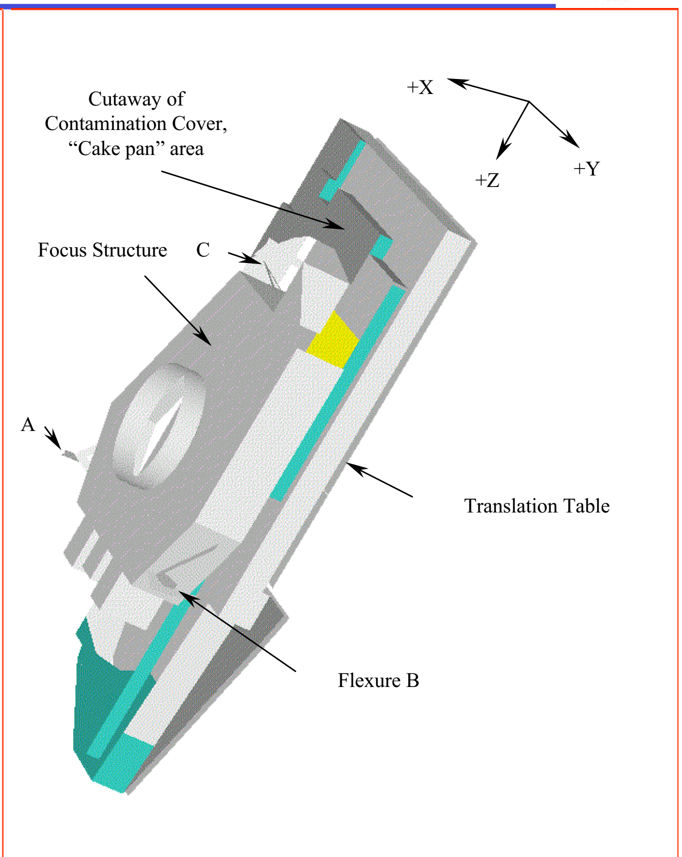
- **SIM WAS A CHALLENGE**
  - One axis translation and focus both required.
  - Very different thermal constraints from the telescope and SI's, with ACIS in particular
  - Needed to be very light-weight, since its mass was at the cantilevered end of Chandra
  - Needed to be ultra-clean

- **REQUIRED INNOVATION**
  - Composite table structures
  - Innovative thermal coatings and adhesions
  - Active thermal control of composite flexures
  - New ways of structurally studying the composite flexures

- **INNOVATIONS BRING PROBLEMS**
  - Bonding and adhesion problems
  - Thermal material cracking
  - Moisture desorption alignment problems
  - Choice of acceptable lubrication

Chandra X-ray Observatory: Challenges





Chandra X-ray Observatory: Challenges

8. **SIM Mechanisms (TECHNICAL)**
   - **RESULT: SIM WAS DELAYED**
     - Weight problem caused late readiness
     - Composite structural integrity testing harder than planned
     - Debonding occurred in first Thermal Vacuum test
     - Themal surfaces cracked during integration
     - Risk of mitigating each was weighed against option of schedule slip
   - **RECOVERY**
     - **LESSON LEARNED**: Define error budgets early and follow them
     - **LESSON LEARNED**: Develop early ICD and iterate/communicate with all parties
     - Developed life test article to demonstrate compliance
     - Kept focus on both schedule awareness and meeting requirements
     - Use competent engineers, especially for alignment
     - **LESSON LEARNED**: Send engineer to plant for critical periods to help move things along

Chandra X-ray Observatory: Challenges

9. X-ray Calibration Facility (XRCF) (ENGINEERING)

- **CHALLENGE: XRCF READINESS**
  - Needed early in the program and used periodically with increasing importance
  - Needed to become world-class clean vacuum facility
  - Required facility modifications
  - GSE for facility needed to be absolutely calibrated and ready to work before testing
    - More accurate than the flight systems
    - Clean as flight but earlier
  - Procedures needed to be developed and certified prior to testing

- **LESSON LEARNED: ASSIGN A SEPARATE ORGANIZATION FOR SPECIAL FOCUS**
  - Could concentrate solely on XRCF as a multi-program facility
  - Selected very competent technical leader with Chandra technical experience
  - Trained them to be sensitive to contamination in everything they did

Chandra X-ray Observatory: Challenges

X-Ray Calibration Facility (XRCF)
Site Plan

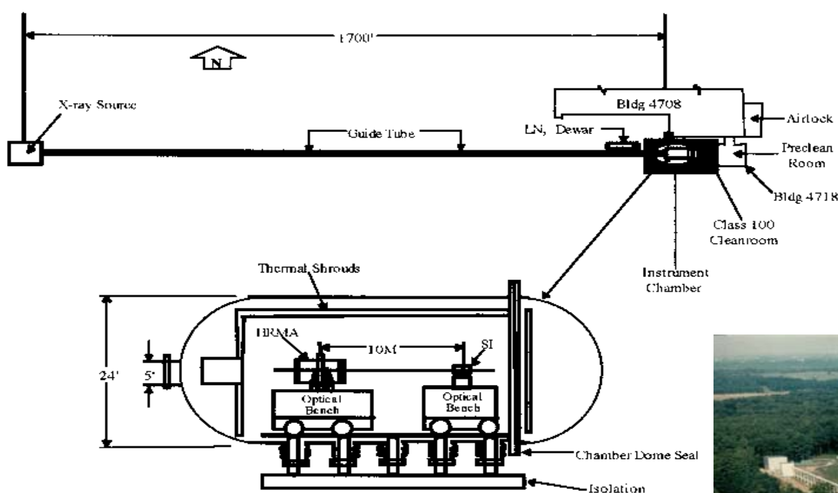
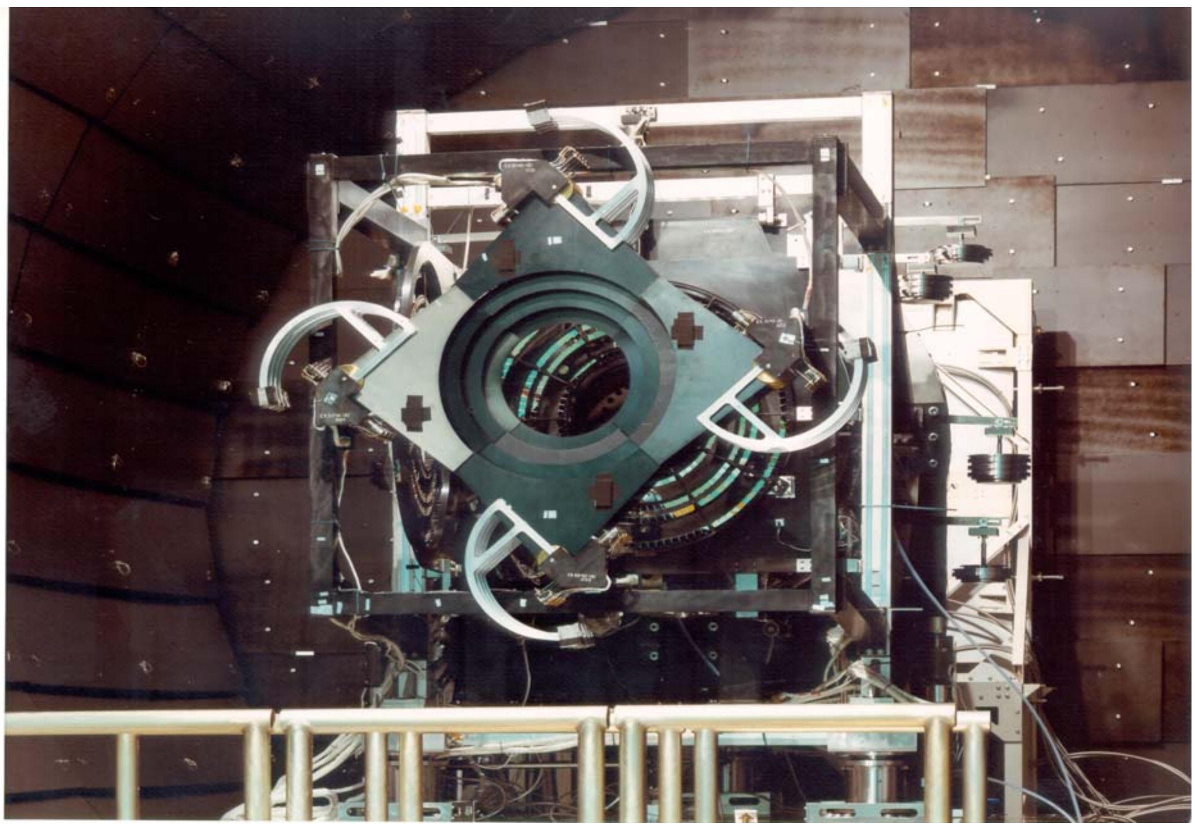


Figure 15

Chandra X-ray Observatory: Challenges



Chandra X-ray Observatory: Challenges

9. **X-ray Calibration Facility (XRCF) (ENGINEERING)**
   - **RESPONSE:**
     - Established frequent tagups to address schedule and worked pro-actively with contractors developing and bringing GSE to the XRCF
     - When HRMA finally arrived, became around-the-clock operation
     - Science had major role; to ensure smooth handoff, had daily shift meetings
     - Shifted into more of a test and integration mindset than hardware development mindset
     - **LESSON LEARNED**: Concentrate on teamwork and communication
     - Work performed equally between XRCF operators, civil servants, contractors, scientists, and instrument personnel.
     - Since time was critical, everyone had an input into the schedule
   - **RESULT:**
     - Ultimately, XRCF performed extremely well
     - It is a world-class facility
     - It is preparing for future calibration work for JWST and Constellation X

Chandra X-ray Observatory: Challenges

10. On-Orbit Proton Radiation (OPERATIONS)

- **ACIS SUSCEPTIBILITY**
  - Prior to launch, it was not expected that ACIS was susceptible to low energy protons and ions
  - Shielding in the HRMA and pre-collimator blocked radiation belts
  - Problem was, HRMA partially reflected ion proton and ion? radiation
  - Protons strike ACIS CCD's and charge loss occurs when electrons are clocked off of the CCD
  - Prior to launch, electron reflections off the HRMA were expected and baffles and magnets were used to sweep electrons from focal path

- **SOURCES**
  - Radiation belts (below 60,000 km)
  - Solar flare
  - Galactic (generally all the time)

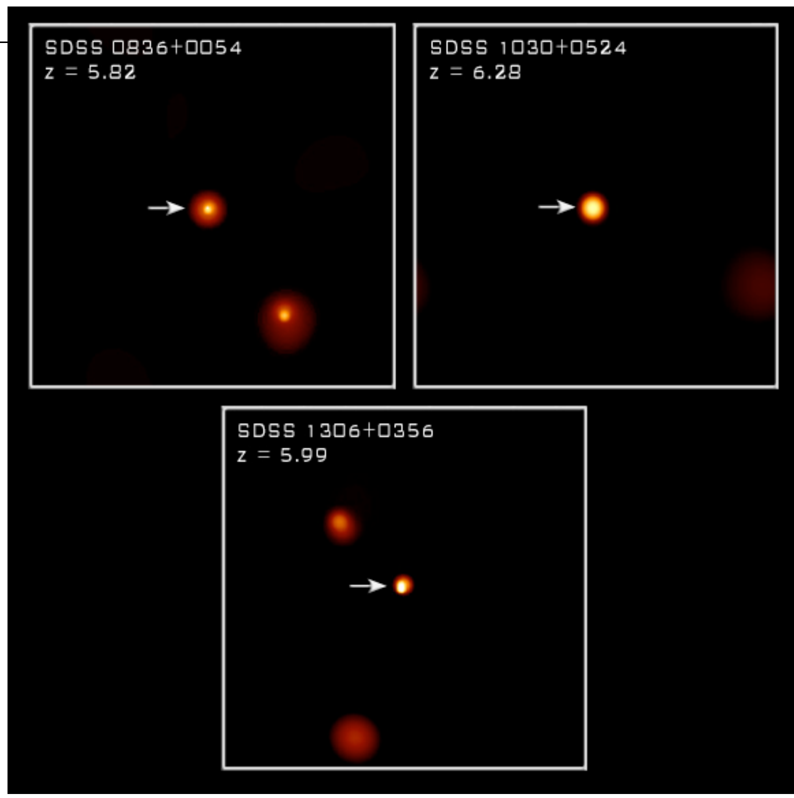
- **MITIGATION**
  - Move SIM to keep ACIS out of beam during threat
  - Develop acceptable error budget for gradual degradation (galactic)
  - Develop early warning system to note environment and react if it is threatening

Backup

Chandra X-ray Observatory: Overview

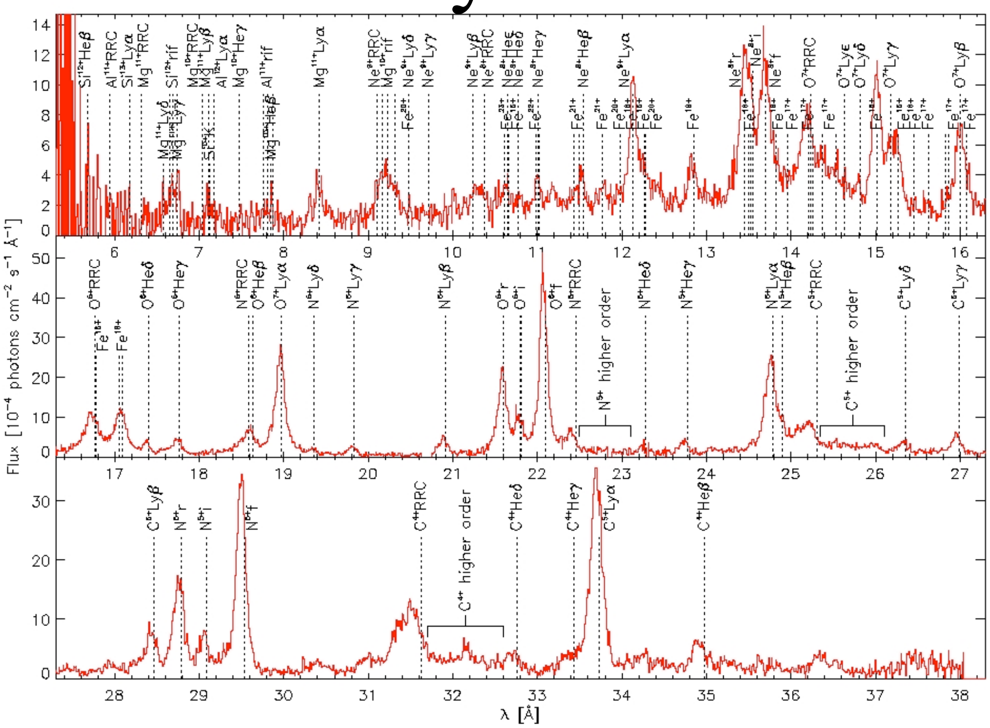
o Launch System:	Shuttle (STS-93) with IUS
o Mirror Configuration:	4 Nested Grazing Incidence Mirror Pairs
o Focal Length:	10 meters
o X-ray Energy Range:	Approx 0.1 keV to Approx 10 keV
o Encircled Energy @ 1 Arcsec:	60% at 0.93 keV at 19% at 8.04 keV (spec; actuals at higher energies are much better)
o Science Instruments:	Advanced CCD Imaging Spectrometer (ACIS), High Resolution Camera (HRC), and 2 movable gratings, one each for low and high energies

X-Ray-Bright Highest-Z Quasars



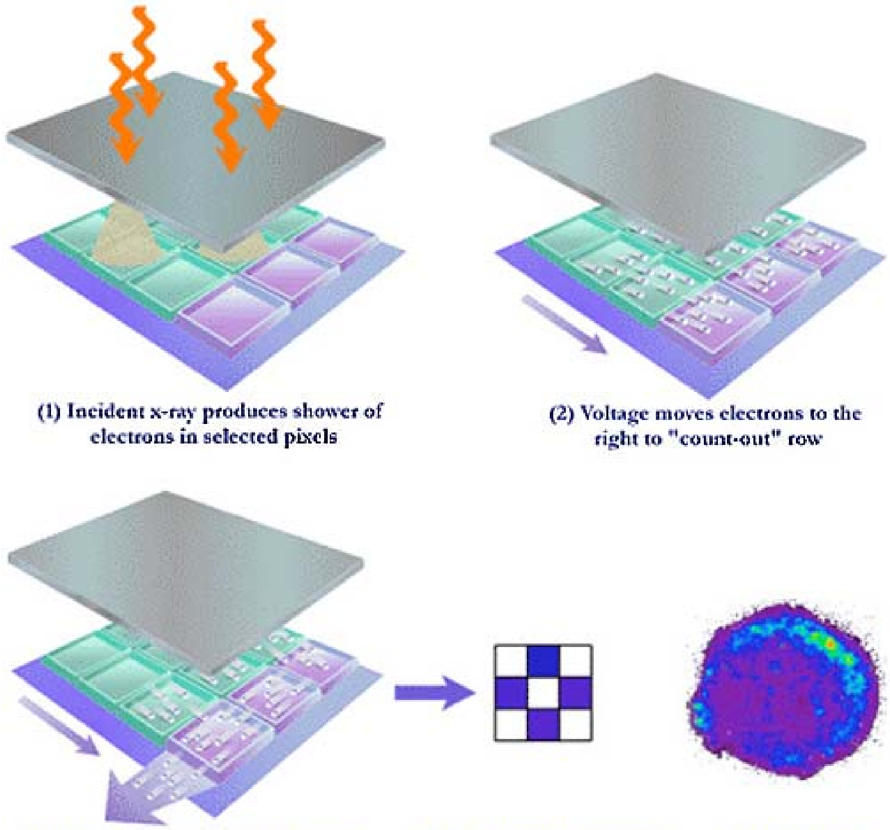
Brandt et al. 2002

The Re-Emitted Line Radiation in Seyfert 2s



Kinkhabwala et al. (2002)

Illustration of CCD



(1) Incident x-ray produces shower of electrons in selected pixels

(2) Voltage moves electrons to the right to "count-out" row

(3) Clocked voltage moves electrons out of count-out row

(4) Computer reconstructs image (9 pixels)

CXC CCD's will have ~ 1 million pixels