My title is: "The Chandra X-Ray Observatory"

My Abstract is: The Chandra X-Ray Observatory, the X-Ray component of NASA's Great Observatory Program has been an outstanding scientific and technical success. Designed for a three year lifespan, Chandra is now beginning its 8-th year of scientific operation. Some of the history of the Project, including a discussion of the design, development, and calibration of the X-Ray optics will be presented. Of course the highlights of several of the myriad discoveries will be shown concerning topics ranging from solar system objects to dark matter studies in clusters of galaxies.
The Chandra X-Ray Observatory

An Overview of its Success

November 14, 2007
Martin C Weisskopf
The Great Observatories

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength (nm)</th>
<th>Energy (eV)</th>
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<td>CGRO</td>
<td>0.0005</td>
<td>2.480,000</td>
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<tr>
<td>HST</td>
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Chandra History Overview

• 1976: Program start
  – MSFC/SAO Collaboration selected by HASA HQ

• 1985: Instrument selection

• 1988: New Start

• 1999: Launch
Crab Nebula
Recipe for Success

- Team effort
- Science-driven requirements
  - Project Science Team
- Stability of requirements
- Technology programs
- Calibration program
Project Science

- More than a single person

- On all review boards --- to level 3
The Observatory

- Solar Array (2)
- Spacecraft Module
- Sunshade Door
- Aspect Camera Stray Light Shade
- High Resolution Camera (HRC)
- Integrated Science Instrument Module (ISIM)
- Transmission Gratings (2)
- Low Gain Antenna (2)
- Thrusters (4) (105 lbs)
- High Resolution Mirror Assembly (HRMA)

CCD Imaging Spectrometer (ACIS)

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• More than a single person
• On all review boards to level 3
Chandra Optics

Field of View ± 0.5 Deg
Focal Surface

4 Nested Hyperboloids
Doubly Reflected X-rays

4 Nested Paraboloids

X-rays

Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

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• 1976 – Proposal was submitted
  – This was the "formal" beginning
AN EXPERIMENTAL PROGRAM
OF EXTRA-SOLAR X-RAY
ASTRONOMY

Prepared for
National Aeronautics and Space Administration
Washington 25, D. C.

Prepared by
American Science and Engineering, Inc.
11 Carleton Street
Cambridge 42, Massachusetts

25 September 1963

Approved:

Ricardo Olescon
Vice President
Space Research and Systems Division

Smithsonian Institution Archives
X-Ray Astronomy

- Solar Studies in late 40's
  - Solar corona produces X-Rays
- Discovery of first extra-solar source in 1962
  - Also discovery of faint glow - the "diffuse" background
Uhuru (SAS-1) Conducted the First All Sky Survey of Cosmic X-Rays in 1971
X-Ray Astronomy

- We now know that most of the matter that we “see” is visible to us from its X-Ray emission
- The bulk of this matter is hot, X-Ray-emitting, gas in the great galaxy clusters
Major New Programs:

#1: An Advanced X-Ray Astrophysics Facility (AXAF)
The Technology Mirror Assembly

- Single mirror pair
- Scaled (2/3) Version of innermost mirrors
- 6-m focal length
  - Allowed for testing in existing test facility
- 0.41-m element length
- 0.42-m diameter
- Gold coated (baseline at the time)
The Technology Mirror Assembly
The Technology Mirror Assembly

• First delivery July 1985
  - Resolution better than 0.5"
  - However, near angle scattering
• Second delivery Jan 1989
• Final results were great
  - E.g. FWHM from 0.36" – 0.68"
  - Encircled energy as predicted
Flight Mirror Blanks

- Initiated purchase in 1987
Other Milestones

- Prime contractor selection – 1988
- "New Start" - 1988
- Selection of the Science Center – 1991
- Started the "VETA" program - 1988
  - Verification Engineering Test Article
• P1/H1 – uncoated and uncut

• Needed test facility at least one year earlier than planned!
The X-Ray Calibration Facility (XRCF)

X-RAY CALIBRATION FACILITY

- ISOLATED FACILITY CONTROL SYSTEM
- SEGMENTED VACUUM SYSTEM
- ADVANCED DATA HANDLING SYSTEM
- ENTRANCE STAGING & BUILDUP AREAS
- TEST CHAMBER
- CLASS 10,000 CLEAN ROOM
- CLASS 2,000 CLEAN ROOM
- USABLE SPACE IS 60' X 20' DIA
- THERMAL CONTROL VACUUM
- OPTICAL 6 SOURCE MONITORING DETECTORS
- POWER SYSTEM WITH EMERGENCY BAY UP
- VIDEO & AUDIO COMMUNICATION SYSTEM
- VERSATILE X-RAY SOURCE & DETECTION SYSTEM

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The X-Ray Calibration Facility (XRCF)
The Veta Tests - 1991

Estimated Mirror Performance on Orbit
Facility Effects Removed Using Lucy Deconvolution of $19 \times 19$ Scan

Energy: 1.49 keV

FWHM = 0.19 arcsec
• 6 months at the X-Ray Test Facility
Three Launch Attempts

- Mon/Tue July 19/20
  - Sensor spike hydrogen in the engine compartment

- Wed/Thurs July 21/22
  - Lightning in the vicinity

- Thurs/Fri July 22/23
  - Third time is a charm
Launch at last! July 23 1999 @ 12:31 a.m.
The Orbit
The Moon

All planets, other than Uranus, are X-ray sources!

- Jupiter
  - Hot spots at high latitudes
    - *Big surprise*
  - Pulsates (45 minute period)
Dark Matter

1E0657-56 Chandra image with lensing contours
Dark Matter & Dark Energy

Cosmological Constraints

\( \Omega_m \) vs. X-ray/SZE Clusters

\( \Omega_{\Lambda} \)

CMB (WMAP)

Scale of the Universe

Present

Future

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Summary

- Operations are running smoothly
- Mission success
  - Design of the Observatory
  - Excellent and committed staff
  - Team effort
- Exciting and fundamental scientific results
  - Papers at a rate of ~10 per week
- Visit our web site @
  www.chandra.harvard.edu
Chandra Lifetime

- Fuel: >40 years
- Orbit: 30-50 years
- Funding: NASA committed to (at least) a 13 year mission