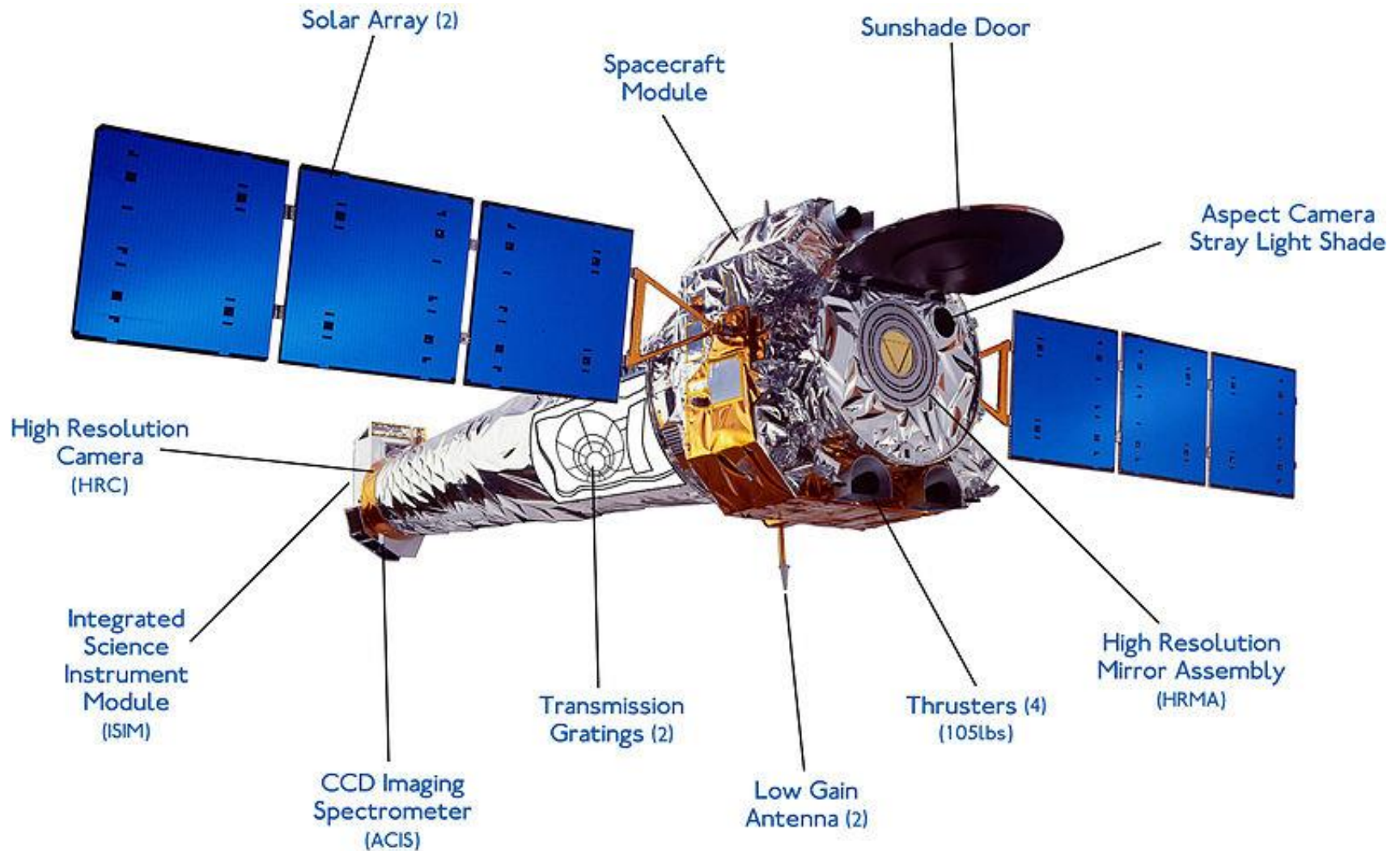


X-RAY OPTICS DEVELOPMENTS AT MSFC

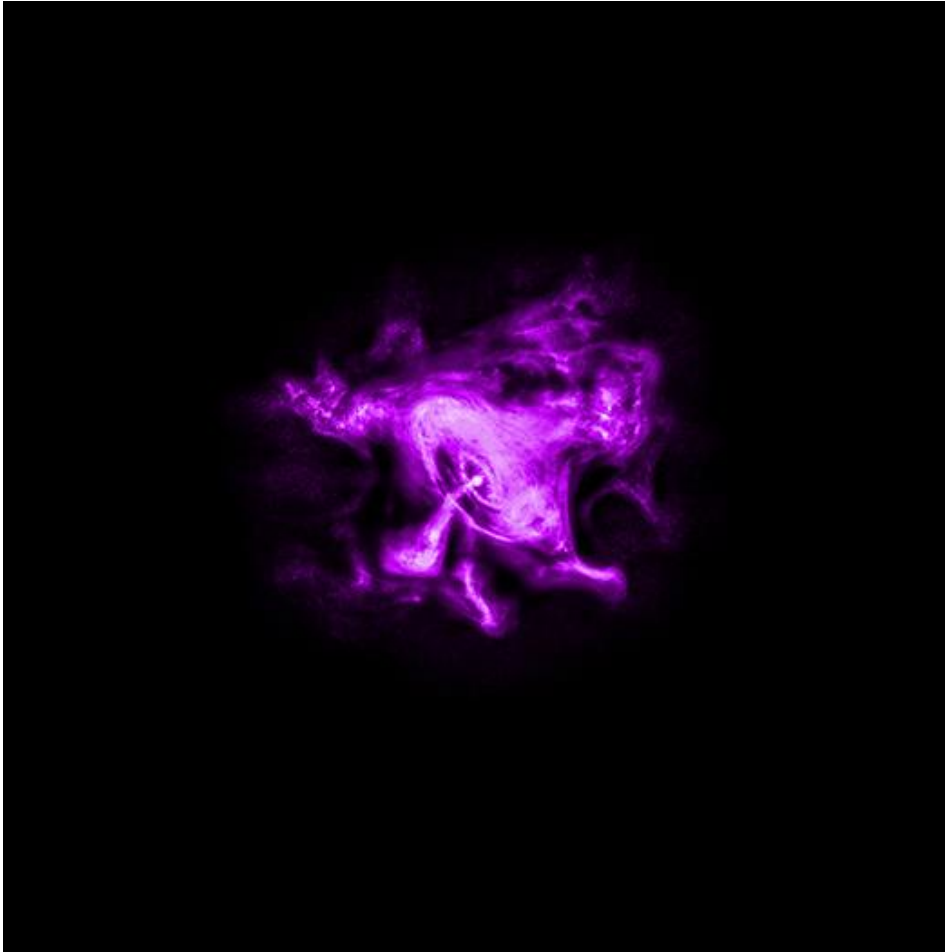
Dharma Sharma on behalf of X-ray Astronomy Group NASA Marshall Space Flight Center

Introduction:

- Development of high resolution focusing telescopes has led to a tremendous leap in sensitivity, revolutionizing observational X-ray astronomy.
- High sensitivity and high spatial resolution X-ray observations have been possible due to use of grazing incidence optics (paraboloid/hyperboloid) coupled with high spatial resolution and high efficiency detectors/imagers.
- The best X-ray telescope flown so far is mounted onboard Chandra observatory launched on July 23,1999. The telescope has a spatial resolution of 0.5 arc seconds with compatible imaging instruments in the energy range of 0.1 to 10 keV.
- The Chandra observatory has been responsible for a large number of discoveries and has provided X-ray insights on a large number of celestial objects including stars, supernova remnants, pulsars, magnetars, black holes, active galactic nuclei, galaxies, clusters and our own solar system.



CHANDRA OBSERVATORY
HIGH RESOLUTION MIRROR ASSEMBLY CONSISTS OF GRAZING INCIDENCE OPTICS
(CREDIT: NASA/CXC/SAO)



CRAB NEBULA (CHANDRA) –CENTRAL BRIGHT SPOT IS THE 33 MILLISECOND PULSAR

**LEFT: X-RAY IMAGE OBSERVED BY CHANDRA TELESCOPE,
RIGHT: COMPOSITE X-RAY, OPTICAL, INFRARED, RADIO AND UV
(CREDIT: NASA/CXC/SAO)**

X-RAY OPTICS DEVELOPMENTS AT MSFC:

MSFC has been developing integrated full-shell X-ray optics for over two decades, which have flown on several missions. At MSFC X-ray full-shell optics (Wolter Type I) are fabricated using electroformed nickel-cobalt alloy. The mirror shells are electroformed onto a super-polished aluminum mandrel and then released by differential thermal contraction. Mirror shells are inherently very stable and reproduce the high-quality surface of the mandrel. The distinct advantages of this process are:

1. Very thin mirror shells can be produced (thickness as low as 50 microns) leading to incorporation of a large number of shells (nested) in each telescope module to obtain large area for increased sensitivity and reduced weight per module.
2. Full shell production of optics by electroforming results in significant cost savings (for example, the cost of the Chandra mirrors was several million and only four (nested) shells were used in a single telescope module!).
3. An angular resolution of better than 10 arc-sec half-power diameter is easily obtainable. A full-fledged program is underway to improve angular resolution by differential coating on the mirrors to correct the reflecting surface of the shell.
4. Shell diameters that range from 2 to 50 centimeters with focal lengths from 1 to 10 meters (and longer) can be produced.
5. Mirror shells can be coated with nickel, gold, iridium, or multilayer for required energy response in the energy range from 0.1 keV to 70 keV.

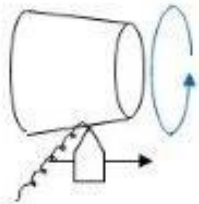
SIMPLIFIED DEPICTION OF REPLICATION BY ELECTROFORMING

Electroformed Nickel Replication

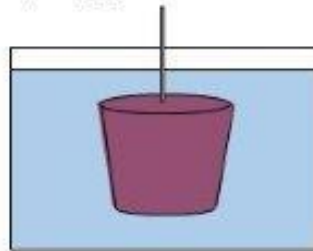


Mandrel Preparation

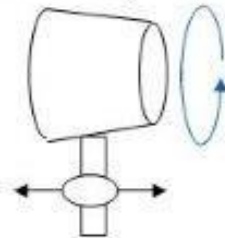
1. CNC machine mandrel from aluminum bar



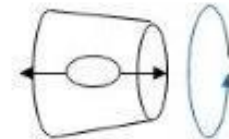
2. Chemical clean and activation & electroless nickel (EN) plate



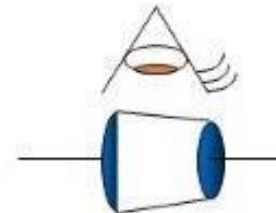
3. Diamond-turn to few 10s nm surface, sub-micron figure accuracy



4. Superpolish to 0.3 – 0.4nm rms finish

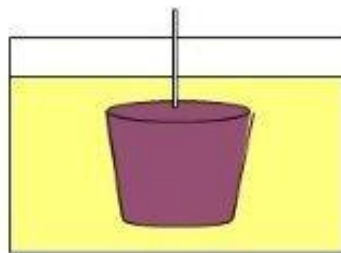


5. Metrology on mandrel

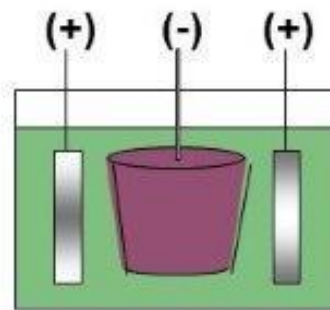


Shell Fabrication

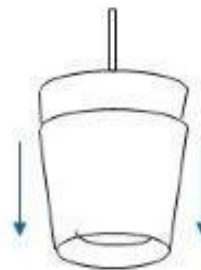
6. Ultrasonic clean and passivation



7. Electroform NiCo shell onto mandrel



8. Separate optic from mandrel in cold water bath



MILESTONES OF X-RAY OPTICS AT MSFC

	<u>IXPE</u>	<u>ART-XC</u>	<u>FOXSI</u>	<u>HERO</u>
Energy range (keV)	2 - 10	5 - 30	5 - 15	20 - 70
Effective area	1000 cm ² @ 3 keV	≥455cm ² @ 8 keV	150 cm ² @ 10 keV	95 cm ² @ 40 keV, 50 cm ² @ 60 keV
Number of Modules	3	7 (plus 1 spare)	7	8
Focal length (m)	4.0	2.7	2.0	6.0
Shells per module	24	28	7	14
Shell diameter(s) (mm)	162 - 272	50 - 150	76 - 103	50 - 94
Coating	No coating	Iridium	Iridium	Iridium
Shell thickness (μ)	180 - 250	250 - 325	250	250

IXPE-Imaging X-ray Polarimetry Explorer, **ART-XC**- Astronomical Roentgen Telescope –X-ray Concentrator, **FOXSI**-Focusing Optics for Solar Imager, **HERO**-High Energy Replicated Optics

(CREDITS: NASA/XPE, WWWASTRO.MSFC.NASA.GOV, WWWASTRO.MSFC.NASA.GOV/LYNX/)



SHELL PRODUCTION BY REPLICATION

(CREDIT: WWWASTRO.MSFC.NASA.GOV, WWWASTRO.MSFC.NASA.GOV/LYNX/)



TELESCOPE MODULE WITH MANY (NESTED) SHELLS (left)
GRAZING INCIDENCE SINGLE MIRROR SHELL (right)

(CREDITS: WWWASTRO.MSFC.NASA.GOV)

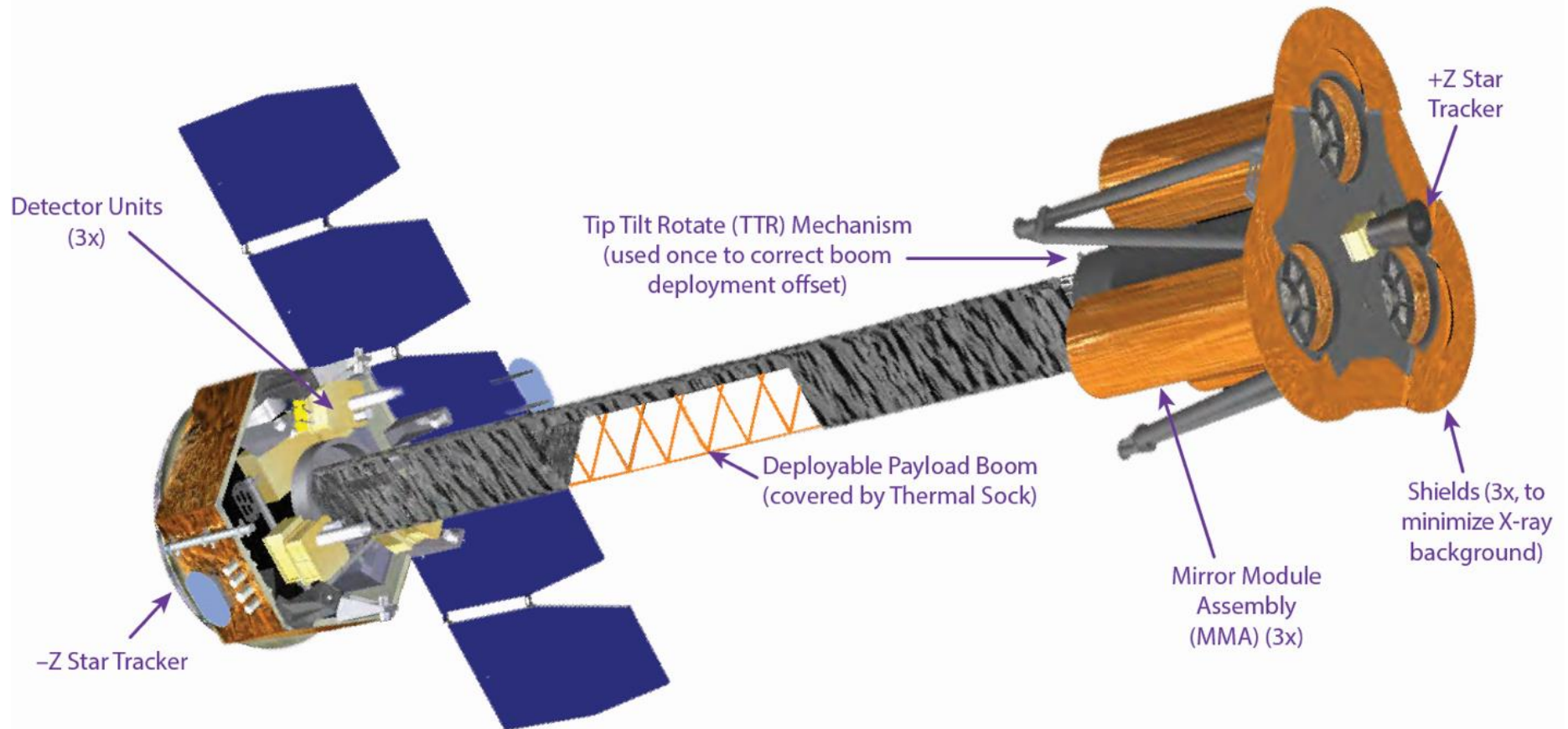


FOXSI FLIGHT PAYLOAD
WITH 7 TELESCOPE MODULES EACH WITH 7 NESTED MIRROR SHELLS
(CREDITS: KRUCKER Et Al 2013, SPIE 8862, WWWASTRO.MSFC.NASA.GOV/LYNX/)



ONE OF THE COATING SYSTEMS AT MSFC

(CREDIT: [GUBAREV/NTRS.NASA.GOV/20150000394.PDF](https://ntrs.nasa.gov/20150000394.pdf))



Mirror Modules consist of grazing incidence optics

IXPE-IMAGING X-RAY POLARIMETRY EXPLORER

**THE MIRROR MODULE ASSEMBLY WILL BE FABRICATED AT MSFC
IT WILL HAVE THREE MIRROR MODULES EACH WITH 24 NESTED SHELLS
EACH MODULE WILL HAVE 250 cm² EFFECTIVE AREA (3-6 keV)**

(CREDIT: [MSFC.NASA.GOV/IXPE/](https://msfc.nasa.gov/ixpe/))

OFF-SHOOTS

1. BUILDING WORLD'S FIRST NEUTRON MICROSCOPE

Cold neutron imaging requires similar graze angles as X-rays, and has potential for many commercial, Homeland Security and defense applications

(CREDITS: GUBAREV M., ET.AL; PROC. SPIE 8147)

2. MEDICAL IMAGING

Non-invasive, functional, small animal imaging for *in vivo* assessment of biological and biomolecular interactions.

The use of grazing incidence optics will be able to achieve resolution much better (<100 microns) than Ultrasound, CT and MRI.

(CREDITS: PIVOVAROFF ET AL 2005, SPIE 5923)