The SuperHERO (Super – High Energy Replicated Optics) High-Angular Resolution, Hard-X-Ray Telescope

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ABSTRACT

The *Super – High Energy Replicated Optics (SuperHERO)* hard-X-ray telescope will observe extended sources at unprecedented imaging resolution, revealing the origins of non-thermal emission in extreme astrophysical environments. As the successor to the *HERO/HEROES* missions, *SuperHERO* builds on over three decades of advancements in NASA Marshall Space Flight Center's replicated NiCo full-shell X-ray mirror technology to deliver better than 10-arcsecond angular resolution (Half-Power Diameter) from a balloon platform: realizing the highest imaging resolution in the hard-X-ray band. The observatory consists of seven identical and co-aligned, 12-meter focal length, mirror assembly telescopes mounted on a carbon-composite, asymmetrical truss. Direct coating of single-layer iridium on the internal surface of the NiCo shells provides an integrated effective area of 45.5 cm^2 at 35 keV. Matching the optics spatial scale requirements, each telescope is paired with a CdTe Double-sided Strip Detector (CdTe-DSD) focal plane that is commercially available from iMAGINE-X Inc. Arc-second level attitude control and pointing are provided by the Wallops Arc-Second Pointer (WASP).

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SuperHERO was selected in the NASA's Astronomy and Physics Research and Analysis (APRA) 2023 call as a five-year mission with a 2-day long initial flight scheduled for the fall of 2028. Launching from Fort Sumner, New Mexico, *SuperHERO* will make detailed observations of the Crab pulsar wind nebula, localizing hard-X-ray emission. A follow-on *SuperHERO* mission will benefit from increased effective area and improved angular resolution. This future mission will propose as a long-duration balloon flight, targeting supernova remnants and galactic binary point sources, and laying the path forward to a high-angular resolution, space-based hard-X-ray observatory.

Keywords: Hard-X-Ray telescope, High-angular resolution X-ray optics, Scientific balloon observatory

1. INTRODUCTION

Non-thermal emission from high-energy astrophysical phenomena often dominates over thermal processes in the Hard-X-ray Band (HXB). Some of the universe's most energetic processes such as Pulsar Wind Nebulae (PWNe), diffusive shock acceleration sites in Supernova Remnants (SNRs), and the combined coronal and jet emissions from supermassive black holes in Active Galactic Nuclei (AGNs) emit significantly above 10 keV. For over a decade, the *Nuclear Spectroscopic Telescope Array (NuSTAR)* space observatory has been transformative, providing critical insights into the hard-X-ray band across a wide range of topics, from the physics of compact objects to the evolution of galaxies.[1] However, *NuSTAR* is ultimately limited by its ~ 1 arcminute angular resolution, which hinders its ability to resolve fine structures in extended sources and to distinguish faint point sources, highlighting the need for a next-generation, high-resolution telescope.[2]

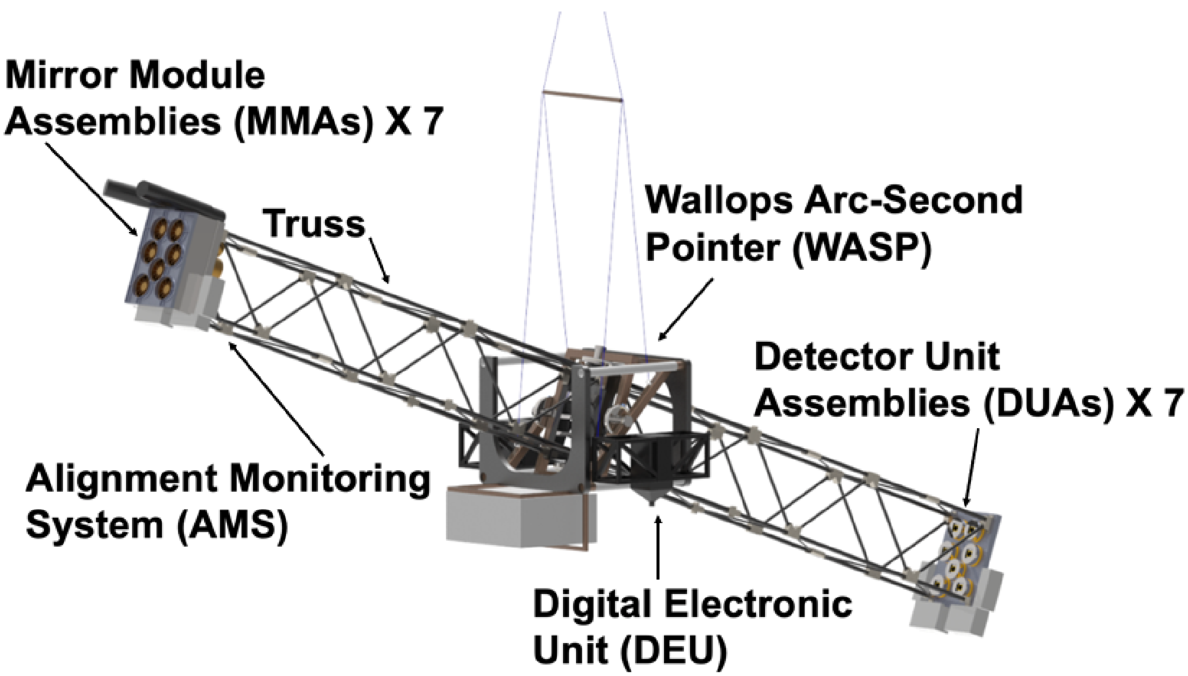

Figure 1. The *SuperHERO* observatory.[3] The Mirror Module Assemblies (MMAs) focus hard-X-rays onto their respective CdTe-DSD focal planes housed in the Detector Unit Assemblies (DUAs), with minor changes in their relative position being monitored by the AMS. The observatory's super-structure is Composite Carbon Fiber Truss and is pointed by the Wallops Arc Second Pointer (WASP).

The Super – High Energy Replicated Optics (SuperHERO) project is a high-angular-resolution, hard-X-ray, balloon-borne telescope mission currently under development. Led by NASA's Marshall Space Flight Center (MSFC), *SuperHERO* builds on the legacy of the *HERO*[4] and *HEROES*[5] balloon missions, the former was the first mission to image astrophysical phenomena using focusing optics in the HXB.[6] Its mission goal is to achieve better than 10 arcsecond (arcsec) half-power diameter (HPD) angular resolution in the HXB. To accomplish this, *SuperHERO* leverages over three-decades of continuous advancements in MSFC's full-shell, replicated NiCo X-ray shell optics.[4,7–13] Iridium coating applied to the inner surface of the NiCo shell increases the X-ray reflectivity to 40 keV.

The *SuperHERO* observatory comprises seven identical, co-aligned telescopes, each with a 12-meter focal length. Each telescope features a Mirror Module Assembly (MMA) constructed from replicated NiCo full-shell optics. Each of the MMAs are constructed with two iridium coated NiCo shells to provide an integrated effective area of 45.5 cm^2 at 35 keV for the entire observatory. Each MMA is paired with position sensitive, Cadmium Telluride Double-sided Strip Detector (CdTe-DSD). These focal plane detectors, developed by JAXA and the Institute of Space and Astronautical Science (ISAS) and employed on the *Hitomi (ASTRO-H)* Space Telescope,[14] are now commercially available through iMAGINE-X Inc.[15] with spatial scale and energy resolution well-matched to the requirements of their partnered MMA. The payload is mounted on a lightweight, open-truss carbon-composite gondola, adapted from the Washington University in St. Louis' (WashU's) *eXtra-Large (XL)-Calibur (XL-Calibur)*[16] mission. To maintain precise optical alignment during flight, the system incorporates a dynamic Alignment Monitoring System, developed by the University of New Hampshire and previously flown on the *XL-Calibur*. High-precision pointing and attitude control are provided by the Wallops Arc-Second Pointer (WASP) system.[17]

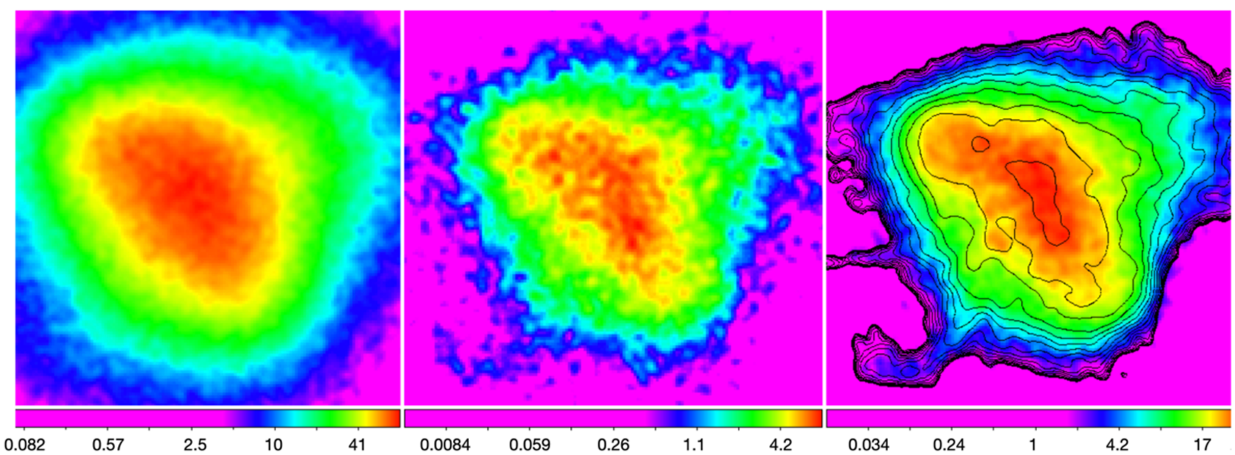

Figure 2. Left: *NuSTAR's* observation of the Carb Nebula with 60 arcsec HPD resolution (20 to 40 keV).[1,18] Middle and Right: projected morphology of the Crab Nebula at 10 and 5 arcsec HPD resolution, as anticipated to be observed by the *SuperHERO* balloon mission and a next generation hard-X-ray space telescope, respectively. Projected images are modeled from soft-X-ray *Chandra* data[19,20] and are expected to have different morphology in the HXB.

Selected through the Astronomy and Physics Research and Analysis (APRA) program, *SuperHERO* officially began its mission on October 1, 2024. Its inaugural two-day flight is scheduled for fall 2028, launching from Fort Sumner, New Mexico. The primary science objective of this flight is to observe the PWN within the Crab Nebula, with the goal of localizing regions of particle acceleration. *SuperHERO* is designed as a pathfinder mission, demonstrating key technologies and performance improvements that will inform and enable future missions. The *SuperHERO* project is designed to provide the basis for iteratively improved payload capability over time through focused technology maturation efforts primarily related to the X-ray mirrors. Notably, *SuperHERO* is being designed to accommodate expanding the number of shells in its MMA's effective area to ~ 100 cm^2 at 35 keV, enabling the science case for a potential, southern hemisphere, Long Duration Balloon (LDB) *SuperHERO* mission. With this in mind, *SuperHERO* is designed to allow for the projected increase in shell mass, necessitating an asymmetrical carbon fiber truss design.

The success of the *SuperHERO* balloon mission, both scientifically and technically, will enable the team to pursue its ultimate goal: a next-generation, high-angular-resolution, hard-X-ray space telescope, with 5-arcsec HPD (or better) imaging capability. This future Medium-Class Explorers (MIDEX) mission concept, the *High*

EneRgy Observatory for Imaging X-rays (HEROIX), will be proposed to achieve science goals that extend well beyond the capabilities of a balloon-borne platform.

2. SCIENCE

Telescope operation on a stratospheric science balloon platform, while challenging, allows for observations to be made in the hard-X-ray band (10 to 80 keV). At an altitude of 39.5 km, Earth's remaining atmosphere is largely transparent to X-rays with an energy greater than 20 keV, providing a window to the high-energy Universe and the astrophysical phenomena that dominate the HXB. For *SuperHERO's* first mission, the telescope will be limited to a two-day – or less – fall flight from Fort Sumner, New Mexico . The astrophysical target of choice both for its high flux and its remarkable science return is the Crab PWN.

2.1 The Crab Nebula

The Crab PWN extended source has garnered the attention of generations of X-ray observatories. Powered by ultra-relativistic winds generated by the rapidly rotating millisecond pulsar at the center of the Crab, synchrotron emission is well into the hard-X-ray band. Multiple high-resolution *Chandra* observations have revealed that the synchrotron radiation starts at the termination shock, where magnetized wind from the pulsar interacts with the ambient medium. Within the inner $\sim$ 10 arcsecs, the surface brightness morphology reveals complex and evolving structures, with *Chandra* localizing the inner ring and knots, and revealing the torus and jet with superb detail in the Soft-X-ray band.[19,20] *NuSTAR* observations of the Crab PWN have shown that it is slightly smaller than in the soft X-ray, likely due to the energy stratification of the synchrotron-generating particles.[18]

The design of the *SuperHERO* observatory is well-suited for a potential future LDB mission with shared hardware and designs. With substantially increased effective area and other improvements, an LDB mission will enable more science opportunities such as resolving the particle acceleration sites in nearby supernovae remnants (e.g., Cassiopeia A for a northern LDB or the Galactic Center region supernovae remnants for a southern LDB) as well as AGN jets (e.g., Messier 87 or Centaurus A). The pathfinder *SuperHERO* missions will pave the path towards future high angular resolution, broad-band X-ray space missions.

2.2 Observation Strategy

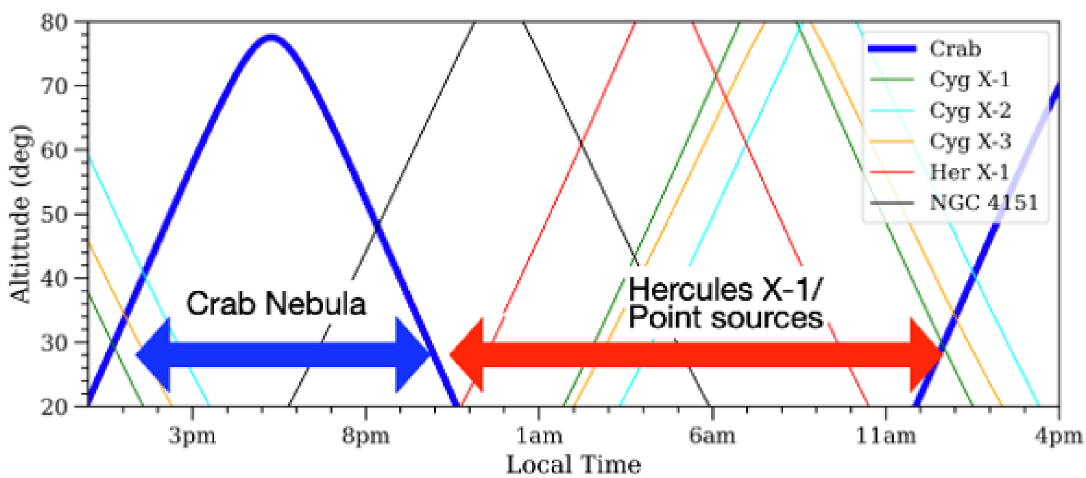

Figure 3. *SuperHERO's* observation strategy for its fall 2028 flight from Ft. Sumner, New Mexico. When observable, the Crab Nebula will be prioritized, maximizing science return. X-ray point sources will be observed when the Crab is not available.

The Columbia Scientific Balloon Facility (CSBF) launches balloon flights from Ft. Sumner, New Mexico in the fall. During this time of year, the Crab Nebula is visible from this location later in the afternoon into the night. *SuperHERO* is anticipated to record 2.7 counts per second in the 20-40 keV band, allowing for

$\sim 70,000$ counts for 8-hours of observation, localizing regions of HXB emission within the extended source with a Signal-to-Noise (SN) > 10. When the Crab Nebula is unobservable, X-ray point sources will be prioritized to characterize *SuperHERO's* angular resolution. The intermediate-mass X-ray binary, Hercules X-1 will be the primary point-source target.

3. INSTRUMENT

The *SuperHERO* mission leverages the strengths of its collaborating institutions to meet its technical requirements. The *SuperHERO's* subsystems, depicted in Fig. 1, are described in the following subsections, along with summaries of their technical capabilities.

3.1 NiCo Replicated Optics and MMAs

To achieve *SuperHERO's* scientific objective of resolving features within the Crab PWN during its first two-day North American flight, the full observatory must achieve an angular resolution better than 10 arcsec HPD and an effective area of 45.5 cm^2 at 35 keV. To meet this requirement, the team is constructing seven MMAs, each containing two high-angular-resolution, coaxial NiCo replicated shells mounted within the MMA's spider structure. The inner and outer shells have nodal diameters of 200 mm and 203.2 mm, respectively, and follow a Wolter-I[21] prescription with a 12-meter focal length. A Wolter-Schwarzschild[22] configuration was also evaluated but was found to offer limited improved resolution across the angular extent of the extended sources, compared to the traditional Wolter-I grazing incidence geometry for this energy band. Each NiCo shell is 1 mm thick to minimize gravity-induced circular deformation errors in the point spread function (PSF). Both the paraboloid and hyperboloid segments of each shell are 300 mm in length, making the total length of 600 mm.

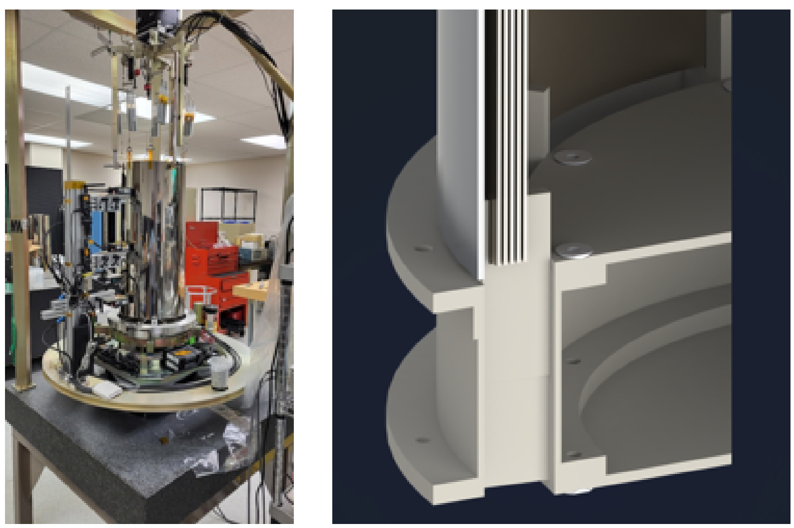

Figure 4. Left: Custom Shell Alignment Station – This precision alignment system is used to mount and bond NiCo X-ray mirror shells into the "spider" support structure. Shells are installed sequentially from smallest to largest diameter, constructing the MMA.[23] Right: Cutaway model of the *SuperHERO* MMA – This model illustrates the modular design of the MMA. For the initial mission, only the two innermost mirror shells will be installed. The structure is designed to accommodate up to three additional, larger-diameter shells for future missions, enabling increased effective area.

SuperHERO's high-angular-resolution NiCo shells are fabricated using MSFC's Electroformed Nickel Replication (ENR) process.[24] The first step involves manufacturing a mandrel—an optical negative of the desired shell. Mandrels are initially rough-cut from 6061 aluminum using CNC lathe machining to a slightly undersized conical approximation. A high-phosphorus electroless nickel (EN) coating is then applied to provide a hard surface suitable for precision diamond turning. The Wolter prescription is cut into the EN layer using the M-40 Moore Diamond Turning Machine, operated by MSFC's ES23 Optical Engineering Department. A similar machine was used for the *Imaging X-ray Polarimetry Explorer (IXPE)*[25] mission. After diamond turning, the mandrel is polished using a conventional pitch-lap lathe to remove tool marks and reduce mid-spatial frequency errors. To further reduce axial figure error and enable sub-10 arcsec resolution, *SuperHERO* mandrels undergo an additional deterministic polishing step using the Zeeko IRP600X. This closed-loop process involves interferometer measurement of the optical surface, followed by deconvolution to generate a tool path that targets areas requiring material removal. The process is repeated iteratively until the error is projected to 2 arcsec HPD or better. A final, non-deterministic, polish using Glanzox high-grade silicon compound brings the surface roughness below 5 Å RMS.

Once the mandrel surface is complete, the mandrel is passivated and placed in a NiCo electroforming bath. NiCo is deposited onto the mandrel surface to form the X-ray reflective shell. The electroforming process is modeled in COMSOL to minimize stress gradients.[26] Upon reaching the target thickness of 1 mm, the mandrel and shell are submerged in cold water. Differential thermal contraction between the NiCo shell and aluminum mandrel causes the shell to release. The mandrel can then be reused for additional replications.

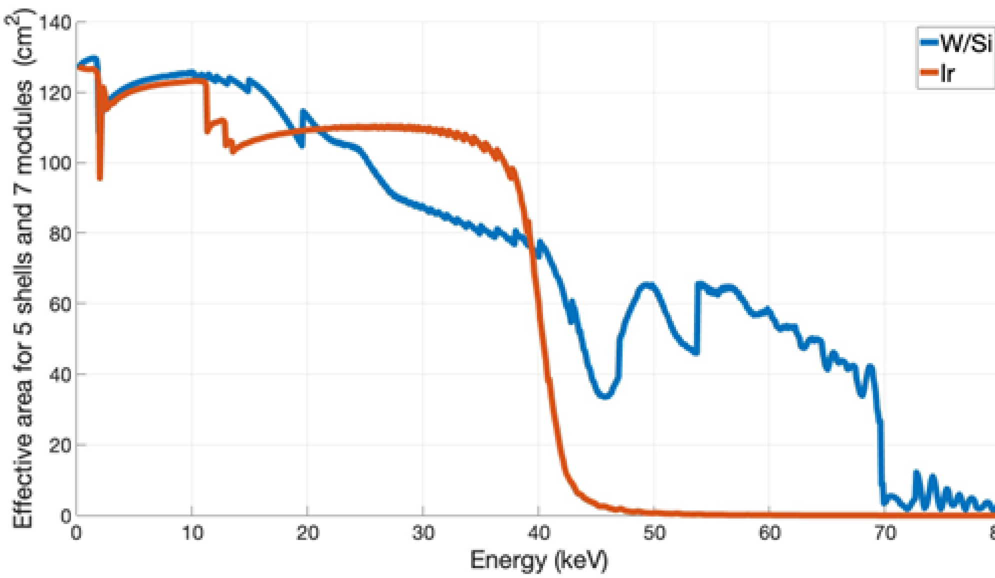

Figure 5. The integrated effective area of a fully realized *SuperHERO* mission, where each of the seven MMAs are fully populated with five shells, is shown. The orange line represents the effective area of the telescope if a single-layer iridium coating is used. The blue line depicts the effective area when depth-graded tungsten/silicon multilayer coatings are applied to the shells. Direct multilayer coating of full-shell optics is currently under development at MSFC. For the 2028 *SuperHERO* flight, only two shells will be installed in each of the seven MMAs. With iridium coatings, the effective area is similar to that represented by the orange line, peaking at approximately 45.5 cm^2 at 35 keV. This figure does not include atmospheric transmission at balloon altitudes, which is largely opaque below 20 keV.

To enhance X-ray reflectivity up to $\sim$ 40 keV, a single layer of iridium is applied to the shell's inner surface using a radio frequency (RF) sputtering chamber. A long, thin iridium target is inserted along the shell's axis and deposits material radially outward onto the rotating optic, ensuring uniform coating. This method was successfully employed for the *Spectrum-Roentgen-Gamma Astronomical Röntgen Telescope – X-ray Concentrator (ART-XC)*[27,28] and *Focusing Optics X-ray Solar Imager - 4 (FOXSI-4)*[29] missions. While the first *SuperHERO* mission will use single-layer iridium coatings, future missions will benefit from a multilayer deposition chamber currently under development at MSFC. A Dual Direct-Cooled Linear DC Magnetron, procured from Angstrom Science through internal funding, will enable concurrent deposition of alternating materials directly onto the shell's interior. This chamber is currently being commissioned. Depth-graded multilayers—such as tungsten/silicon (W/Si)—will be explored to extend reflectivity up to 69 keV for future missions.

After the shells have been replicated and coated, they are sequentially bonded to a common structure referred to as a spider, to create an MMA. A custom shell alignment station was developed for the *IXPE* program and recently used for *FOXSI-4* and *FOXSI-5* sounding rocket missions. The shells are installed inner to outer and the contribution to the HPD from the assembly process is less than 1 arcsec.[23] As discussed, each of *SuperHERO's* seven MMAs, for the first mission, will only have two shells. For potential future missions, *SuperHERO* will require ~ 100 cm^2 at 35 keV to achieve its science goals, requiring that each MMA has five shells, and the manufacture of three additional mandrels. Accordingly, the *SuperHERO* MMAs have been designed to accommodate three more shells.

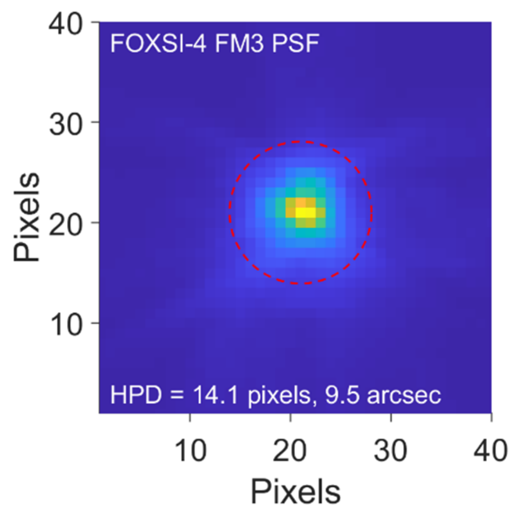

Figure 6. The PSF of the fully integrated FOXSI-4 MMA.[29] Data were collected at the Marshall 100-Meter X-ray Beamline, a horizontal facility. The MMA's resolution is projected to be 5 - 7 arcsec when not under the influence of gravity.

Currently the highest angular resolution achieved by a fully integrated MMA using MSFC replicated shells is projected to be 5 - 7 arcsec,[29] without the influence of gravity, manufactured for the *FOXSI-4* mission. Pre-flight calibration of all *SuperHERO* MMAs will be conducted at the Marshall-100/Stray Light Test Facility.[30]

3.2 Hard-X-Ray Focal Plane and Detector Unit Assembly

The iMAGINE-X Inc. CdTe-DSDs employed on *SuperHERO* are based on the design used on the Hard-X-ray Imager (HXI) flown on *Hitomi*.[14,31–33] Each detector is composed of a 1 mm thick, 34 $\times$ 34 mm^2 CdTe block. 128 platinum cathode and aluminum anode strips are applied to the top and bottom, respectively, of the CdTe block, forming a Schottky barrier between the electrodes and the substrate. Running orthogonal to each other the cathode and anode strips are 200 μm wide and have 250 μm pitch, providing a total collecting area of 32 $\times$ 32 mm^2. The CdTe-DSD is mounted directly to its own dedicated Application Specific Integrated Circuit (ASIC), and has an operational temperature $-20\,^{\circ}$C $\pm$ $5\,^{\circ}$C. The potential between the cathode and anode strips is held at 250 V, with final temperature and bias to be determined in preflight calibration. The energy bandpass of the CdTe-DSD is $>$ 80 keV, accommodating all of *SuperHERO* science range.

X-ray events absorbed in the CdTe produce electron/hole pairs that are proportional in number to the energy of the incident X-ray. The high voltage causes the electrons and holes to propagate to cathode and anodes strips, respectively. Single strip events, where the charge is only registered by one strip, accounts for 70–80% of all incident events, the remaining 20–30% of events impart charge on two adjacent strips.[33] Interpolating the ratio of these 'two-strip' events allows for improved spatial resolution of the X-ray interaction location. The interaction localization is $\sim$ 200 μm, corresponding to 3.4 arcsecs in *SuperHERO's* plate scale, providing a factor of 3 oversampling of the HPD. The CdTe-DSD ASIC board is read out at a rate of 5 kHz by the SPMU-001 board, which incorporates a Xilinx SPARTaN-7 FPGA. Data from the SPMU-001 is transmitted out of its housing, the Detector Unit Assembly (DUA), via SpaceWire to another SPMU-001 unit located in the Detector Electronics (DE), which is positioned near the DUAs. This SPMU-001 links to a small-form-factor, Linux-based CPU via

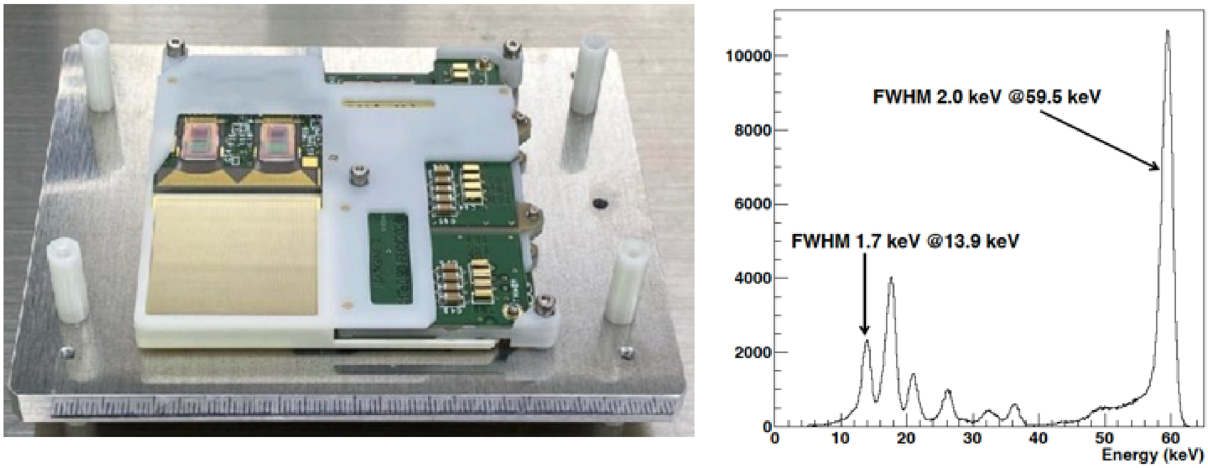

Figure 7. Left: The CdTe-DSD is based on the focal plane used in the HXI aboard the Hitomi space telescope and is now available through iMAGINE-X Inc. Right: The energy response of the CdTe detector[33] aligns well with *SuperHERO's* bandpass.

100Base-T Ethernet, also housed within the DE. The integrated DE system buffers the data output from the CdTe-DSD and then transmits it to *SuperHERO's* avionics system through an 100Base-T Ethernet cable routed up the carbon fiber truss. A single DE unit can read out the output of four CdTe-DSDs, necessitating the use of two DE units for *SuperHERO's* first mission. This architecture is based on a similar design successfully employed on the *FOXSI-4* sounding rocket mission.[34]

The CdTe-DSD is housed in the DUA, currently under design. The DUA provides the thermal control and bias voltage, and additionally houses the readout electronics required to operate the CdTe-DSD. The DUA is a sealed enclosure, held at 1 atmosphere of dry Nitrogen. This is done to stop condensation from damaging the CdTe-DSD and to prevent coronal discharge arching across the biased cathodes/anodes and destroying the detector. The CdTe-DSD is placed directly behind a hard-X-ray transparent beryllium window. The DUA mounts Graded-Z shielding around the detector plane, reducing the background.

A single CdTe-DS, with a 32×32 mm^2 active area, covers a 9.2 arcmin Field-of-View (FoV) at *SuperHERO's* 12-meter focal length. This is sufficient for covering the Crab PWN, but limiting for future LDB missions. The DUAs are being designed to take advantage of the abuttable feature of the CdTe-DSD. Future configurations can arrange the CdTe-DSD in a 2 x 2 array expanding the focal plane to 64×64 mm^2, taking full advantage of *SuperHERO's* FoV provided by its hard-X-ray optics.

3.3 Truss and Alignment Monitoring System

SuperHERO's composite carbon fiber truss draws extensively from the truss employed successfully on the *X-Calibur*[35] and *XL-Calibur*[16] balloon missions. Carbon fiber tubes enable both the mechanical rigidity coupled with exceptionally limited thermal expansion properties required for long focal length X-ray telescopes, while minimizing mass. Both the front and rear of the truss terminates into aluminum honeycomb panels that mount the seven MMAs (front) and their corresponding seven DUAs (rear). The truss structure is manufactured to its custom length by linking carbon fiber tubes by epoxying them into custom designed aluminum inserts. The truss is being designed to meet the WASP requirement that the frequency of the lowest vibration mode exceeds 10 Hz. The Truss is being manufactured by WashU with assistance from the rest of the *SuperHERO* team.

The truss mounts to the WASP gondola pointing system at its center of balance. For the first mission, both the DUAs and the MMAs (each with two NiCo shells) have an integrated mass of ~ 100 kg, necessitating a symmetrical truss where the WASP interfaces with the truss at, or near, its center. However, with the anticipated increase of shells required to meet the necessary effective area to accomplish future mission science goals, the MMA integrated mass will increase to ~ 200 kg. Accordingly, the truss is currently under designed to meet the

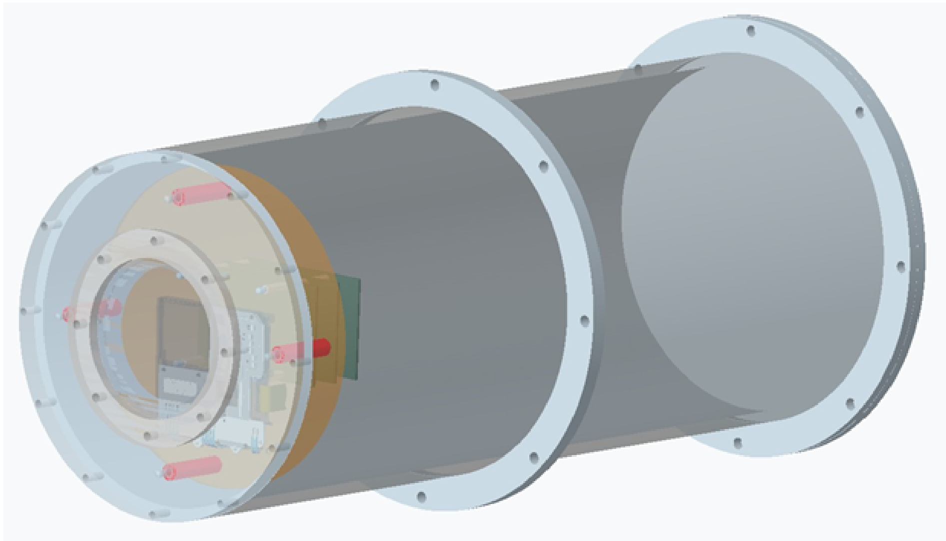

Figure 8. The Detector Unit Assembly (DUA): *SuperHERO's* seven DUAs each house a CdTe-DSD focal plane detector and provide thermal control.

requirements of a potential future mission. The asymmetrical truss design interfaces with WASP gondola closer to the MMAs, reducing the mass required to balance the truss.

The truss is expected to have a slight, elevation dependent, bend where the relative position and alignment between a MMA and its DUA changes. During the *X-Calibur* and *XL-Calibur*, rear-facing, commercially available video cameras mounted on its optic side of the truss recoreded the position of Light-Emitting Diode constellation mounted near its detector plane. Using this approach *XL-Calibur* monitored the position of the on-axis focal spot to a precision of < 0.1 mm.[36] *SuperHERO* will employ a similar system to monitor the position of all seven focal points relative to the position of their MMAs. This system is being led by the University of New Hampshire (UNH).

SuperHERO will utilize the WASP system,[17] which is a high-accuracy attitude control system provided to the ballooning community. Based out of the Wallops Flight Facility (WFF), the WASP system provides arcsec-level attitude control and point-knowledge solutions. It has previously been deployed on the X-ray missions *X-Calibur* and *XL-Calibur*, along with other balloon missions that have required high pointing accuracy.

3.4 Digital Electronics Unit and Avionics

SuperHERO's avionics system is known as the Digital Electronics Unit (DEU). The DEU incorporates a combination of commercial off-the-shelf and custom-designed components and is based on a similar architecture previously used for the second-generation *Extreme Universe Space Observatory on a Super-Pressure Balloon (EUSO-SPB2)*[37]I mission. The DEU is responsible for controlling and recording data from the DUAs, collecting housekeeping data, managing the AMS, and providing regulated voltage to the *SuperHERO* payload. It also controls the heaters. The DEU communicates directly with the Columbia Scientific Balloon Facility (CSBF)-provided Consolidated Instrument Package (CIP), through which truncated science data is transmitted. To prevent condensation, the DEU is housed in a sealed enclosure maintained at 1 atmosphere of dry nitrogen.

4. SUMMARY

SuperHERO is a balloon-borne hard X-ray telescope designed to achieve focused imaging with better than 10 arcsec HPD in gravity, actualizing the highest angular resolution ever achieved in the hard-X-ray band. As the successor to the *HERO* and *HEROES* missions, *SuperHERO* builds on over 30 years of technology development in MSFC's replicated NiCo shell optics. The mission integrates high-heritage technologies from multiple collaborating institutions, including a carbon fiber truss developed by WashU and the AMS structure

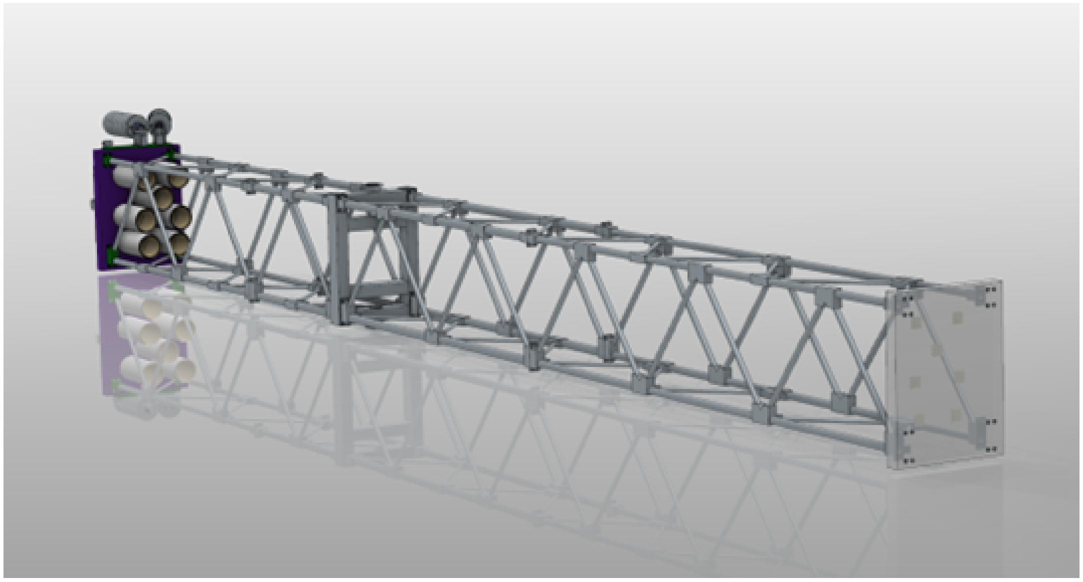

Figure 9. *SuperHERO's* asymmetric composite carbon fiber truss is engineered to support the anticipated increase in mass from future additions to the MMA. The truss is mounted to the WASP at its center of mass, positioned closer to the MMA to maintain balance and pointing stability.

developed by the UNH, both originally designed for the *XL-Calibur* balloon mission. The WASP system, developed by NASA WFF, enables arcsec-level pointing precision. *SuperHERO* also incorporates CdTe-DSD focal plane detectors developed by JAXA/ISAS and Kavli-IPMU and now available commercially from iMAGINE-X Inc., along with avionics developed at MSFC.

A two-day North American flight is scheduled for Fall 2028, during which *SuperHERO* will localize non-thermal emission structures within the Crab Nebula. This mission will pave the way for future long-duration balloon flights and space-based observatories with enhanced scientific capabilities, such as the proposed *HEROIX* mission concept.

4.1 Acknowledgments

The authors wish to acknowledge the efforts of Kurt Dietz, Miguel Rodriguez-Otero, Carl Benson, Kirtan Dixit, Ryan Upton, Jagan Ranganathan, Steve Cheney, Bruce Weddendorf, Stephany Andrews, Amberly Stapler, Mark Massey, Jana Savanapridi, Andrea Green, Darron Rice, Karen Mitchell, Victor Guarino, Hamta Farrokhi Larijani, Ed Udinski, and Neil Martin for their contributions to the *SuperHERO* mission. I.L was funded by the European Union ERC-2022-STG - BOOTES - 101076343. Additionally, we wish to thank the continued support of the Astrophysics Research and Analysis (APRA) program for its ongoing commitment to the mission.

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