Brainstorming Session #2

Technology

Tech from Moon, Mirrors, Detectors
Industry Partnership, Software

Introduction: Future Technology Opportunities for NASA Astrophysics

- **New observing platforms - The Moon:** Science instruments hosted on the lunar surface and other novel environments (Scott Porter, Jenna Cann, Richard Green, John Conklin, Tabby Boyajian)
- **Advances in optics:** New technologies, materials, fabrication and optical assembly techniques (Dustin Swarm, Kristin Madsen).
- **Advances in detector technology:** Next-generation detectors enabling higher sensitivity, broader energy coverage, and improved energy resolution and polarization sensitivity Carolyn Kierans, John Tomsick, Johanna Nagy).
- **Innovative mission approaches - Industry partnerships:** Partnerships with industry and increased use of off-the-shelf technologies (John Arenberg, Rita Sambruna, Michelle Hui).
- **Software and pipelines:** Mission software, onboard processing, calibration frameworks, simulation tools, and end-to-end data analysis pipelines (Adam Goldstein, Johannes Eser).
- **AI and data science:** Applications of artificial intelligence in mission design, data analysis, and theoretical modeling.

Group Moderators

- Group #1 Tech from Moon: Scott Porter, Jenna Cann, Richard Green, John Conklin, Tabby Boyajian
- Group #2 Mirrors: Dustin Swarm, Kristin Madsen
- Group #3 Detectors: Carolyn Kierans, John Tomsick, Johanna Nagy
- Group #4 Industry Partnership: Jon Arenberg, Rita Sambruna, Michelle Hui
- Group #5 Software: Adam Goldstein, Johannes Eser

Group 1: Tech from Moon

- What technological advances have there been in the last 5 years?
  - Landers, CLPS, launch vehicles, Artemis
- What areas are poised for big advances in the next 5 years?
  - Large scale lunar infrastructure, possibly of benefit to Astrophysics
  - Power generation + thermal management (two week lunar night)
  - Advances in robotic manufacturing and assembly (3D printing)
  - Develop international partnerships to make this all possible

Group 1: Tech from Moon

- Is there a compelling case for Astronomy/Astrophysics from the moon? (Topic has a long history)
    - Do you need the moon?
        - Unique platform?
            - Low frequency radio telescopes → really a unique place, but need a radio-quiet moon.
            - Gravitational wave: Lunar-based GW detectors in the Mid-band spectrum (LILA, LGWA) for high-latency multi-messenger follow up campaign
            - Stability of the moon for optical telescopes, cosmic ray experiments, interferometry
            - X-ray optics - could open up new parameter space for higher sensitivity/res than possible from satellites (mass restrictions…assuming that there is a cost-effective way to get that mass to the Moon in the first place)
    - Can you do science from the moon
        - As long as you are going anyway…
        - Almost any space telescope could, in principle, be sited on the moon.
        - Trade-offs → e.g., lose FOV, but with Artemis infrastructure, could have better communications, data bandwidth
- Is it cost effective?
    - depends on the boundary conditions, i.e. what infrastructure can you take advantage of?
- What are the boundary conditions?
    - Who provides transportation, power, comms, i.e. infrastructure

Group 1: Tech from Moon

- What areas are lagging but needed for the science / missions you'd like to see in the next decade?
  - Gravitational wave detection
    - Precision laser interferometry on the lunar surface
    - Low-frequency seismic noise characterization of the Moon
  - Infrastructure for large telescopes
  - On-site fabrication for radio telescopes (wire, for example)
  - Support infrastructure - sustained power to survive lunar night, instrument protection (dust, temperature changes, etc.), robotic assembly
- What do you see the role of AI being in relation to astrophysics technology?
  - Automated alignment for high-precision laser interferometry and active environmental noise cancellation for GW detectors on the Moon
  - Autonomous pointing and data reduction for telescopes
  - Optimize use of resources, comms, power, etc.

Group 2: Mirrors (X-rays)

- What technological advances have there been in the last 5 years?
    - Mirror coatings for improved throughput, low stress
    - Broadband multilayers and multilayer materials
    - Mounting and alignment for full shells
    - Direct polishing improvements
    - Silicon pore optics at ~TRL 6. Lightweight optics
    - Lobster-eye optics (wide field of view) have been successfully flown
    - Small platform optics (e.g., cubesats)

Group 2: Mirrors (X-rays)

- What areas are poised for big advances in the next 5 years?
    - Mass fabrication of mirror components is important across optics designs
    - Segmented optics
        - Mounting, alignment, coating for segments -> Mirror module
        - Engagement of industry partner to solve mass production issues
    - Full-shell optics
        - Improving surface replication process
        - Expanding ranges of radii available for replication
    - Lobster-eye
        - Improved angular resolution
    - What areas are poised for big advances in >5 years?
        - Laue lenses for hard X-rays
        - Gamma-ray multilayer-coated focusing optics
        - Milliarcsecond resolution through X-ray interferometry

Group 2: Mirrors (X-rays)

- What areas are lagging but needed for the science / missions you'd like to see in the next decade? (What is holding us back?)
  - Money and time - We have shown performance of individual units/modules, but integrating modules or improving mirror quality takes money and time that is not available
  - Moving from individual units to manufacturing scale vs. starting from holistic system and tuning to individual cases
  - Industry partners could help with challenges, but are expensive. How do we pay for this or incentivize partnership?
  - We have solved many technology challenges but need to scale these productions
  - US process currently is small funding streams. Success of SPOs is ESA provided large amounts of money and time. Suggest adopting ESA model for technology development. **We need *funded* mirror maturation programs.**
- What do you see the role of AI being in relation to astrophysics technology?
  - Polishing feedback
  - Alignment diagnostics and improvement
  - Real-time feedback on multilayer coating design

Group 3: Detectors

- What technological advances have there been in the last 5 years?
  - X-ray
    - CZT detectors (15-20 years) – NuSTAR 2012 launch, AstroSat CZTI
    - Gas electron multipliers (15-20 years) – IXPE 2022 launch
    - Micro-calorimeters (15-20 yrs) - XRISM
      - Large TES arrays (within the last year!) - Athena Demonstration model
  - Gamma-ray
    - Silicon Photomultipliers (SiPMs, ~5 yrs) – GRID, SIRI-1/2, GARI-1/2, Glowbug, GECAM, COSI
    - Thick (>1 cm) CZT with excellent spectral resolution - ComPair (virtual Frisch-grid), TERI on ISS (pixels)
    - Double-sided strip GeDs (15-20 years) – COSI 2027 launch
    - Liquid scintillators (Ar) with high resolution readout – e.g., GammaTPC, GRAMS
  - mm, sub-mm, and far-IR
    - Transition-Edge Sensors (TESs) - Many large arrays fielded for ground-based and balloon-borne CMB experiments. Microwave SQUID multiplexing demonstrated with Simons Observatory (but high power).
    - Microwave Kinetic Inductance Detectors (MKIDs) - ground and balloon demonstrations. Significant developments for space with PRIMA. Potentially higher packing density than TESs
    - Thermal KIDs (TKIDs) - early demonstrations.
    - On-chip spectrometers - enabling line intensity mapping (LIM)
  - Optical
    - MKID developments - photon-counting (and energy-resolving) KIDs in early development.
  - (Other wavelengths were not well-represented in this group :( )

Group 3: Detectors

- What areas are poised for big advances in the next 5 years?
  - Integrated readout to get larger focal planes is a common theme across all wavelengths
    - Front-end SQUID fab combined with TES detectors (x-ray) and CMOS monolithic silicon sensors (gamma-ray)
  - X-ray
    - Pixelated CZT detectors with broader bandpass (**0.2**-200 keV) – mainly reducing noise to get to lower energies and improve energy resolution
    - Finer spatial resolution for TES detectors
    - Magnetic calorimeters
  - Gamma-ray
    - Thick, highly segmented CZT to increase the bandpass to the MeV range
    - Halide perovskite technology (e.g., MAPbI3) – early TRL concept to distinguish between X/gamma-rays and charged particles for TDAMM
    - TES microcalorimeters operating at gamma-ray energies for insane energy resolution
    - Improvements in SiPM technology for radiation hardness and low power
    - CMOS monolithic semiconductor detectors at higher energies (~>100 keV) - e.g. AstroPix
  - mm, sub-mm, and far-IR
    - Demonstrations with PRIMA and LIM experiments

Group 3: Detectors (readout, cryotech, filters, instrument)

- What else needs to be done to take advantage of detector advances?
  - Readout
    - Multiplexing (time or frequency) – many input signals into one channel
      - For example, multiplexed SQUID readout for TESes
    - Fast frame rates – for example, to avoid pileup for high rates
    - MKIDs for CMB and far-IR, as well as LIM with on-chip spectrometers,
    - New high-speed radiation-tolerant FPGAs coming online
  - Cryo/thermal technologies
    - Need low power coolers for sub-K detectors and ~1-4 K cryocoolers to back them
    - Thermal management of large apertures, and relatedly optical blocking filters for X-ray instruments

Group 3: Detectors

- What areas are lagging but needed for the science / missions you'd like to see in the next decade?
  - Investment in CMB technology, especially cosmic ray mitigation and CMB-focused low-power readout (higher multiplexing with low power)
  - Funding for supporting technologies for x-ray: e.g. aperture blocking filters, milli-K coolers
  - Large effective area concepts for gamma-rays, with higher efficiency detectors than current technologies, while maintaining low noise, low power, broad energy range
  - **Combined** low power, high resolution, high efficiency detectors
  - Different wavelengths don't talk but we can learn from each other!
- What do you see the role of AI being in relation to astrophysics technology?
  - Can see a significant role for machine learning for gamma-ray instruments (e.g., Compton and pair production telescopes)
  - Potential applications for detector screening and instrument calibration
  - Cosmic ray removal and other on board data processing for space missions

Group 4: Industry Partnership

- What technological advances have there been in the last 5 years?
  - Constellations
  - Robotic servicing (replacing hardware, docking / refueling) -> mission life extension
  - Modern Manufacturing -> 3D printing space-rated parts
  - Launches: bigger, more frequent, rideshare (CLPS)
  - Communications (commercial network, optical comm)
  - AI in operations
  - Solar sail
- What areas are poised for big advances in the next 5 years?
  - Power beaming
  - Manufacturing: In-space
  - Communication infrastructure: intersatellite, large data volume
  - AI in operations and computing
  - Commercial space stations

Group 4: Industry Partnership

- What areas are lagging but needed for the science / missions partnership you'd like to see in the next decade?
    - Programmatic: Less oversight and more flexible;
        - “agile management” style
    - Efficiency: standardize spacecraft for multi-missions -> people and design cycles are the cost and schedule driver
    - Design Approach: a probability/average time to failure for example
    - More engagement between the NASA science community and industry
    - Leveraging bulk economies → may need multipurpose goals
- What do you see the role of AI being in relation to astrophysics technology?
    - Streamlining operation
    - System engineering

Group 5: Software

- What advances have there been in the last 5 years?
  - Cloud computing - Roman Research Nexus, SciServer, Fornax
    - Learning to interface with data in a different way
  - Statistical Methods
  - Beginning to adopt AI/ML
  - Open data/software
  - Recognition in software development has improved, but still needs to continue to improve
    - Zenodo, DOIs, citations, GitHub
  - Rapid response and alerts have advanced and are necessity for Rubin

Group 5: Software

- What areas are poised for big advances in the next 5 years?
    - Cloud computing - data lakes
    - On-board computing - more powerful onboard analysis - could use AI/ML
    - Differentiable programming utilizing GPUs - simulations, N-body problems, etc.
    - Use of LLMs for coding and documentation
    - AI/ML for instrument calibration and scientific analysis
    - Continuing community development of analysis tools

Group 5: Software

- Challenges
    - Transmission data volumes - (may be relieved by on-board computing or better comms)
    - On-ground data volumes, access, and cost - Roman is sort of pathfinding this for NASA, also Fornax Initiative
        - Also maintaining ability for scientists to download/analyze locally when it makes sense
    - Uploading data to the cloud - databases/archives talking to each other
    - Difference between open and “supported” software - what is needed is documentation, funding
        - Software is often treated as an afterthought when costing a new mission and is the first thing to get squeezed with budget overruns…and schedule overruns
    - Trade-off in quality with on-board processing dependent on science cases
    - Standards (alerts, formats, cloud/archive)
    - Propagation of calibration uncertainty and data versioning through L1 -> L2 -> ....
    - Possibly evolving release models of official analysis software - What best serves the community?
    - Funding support and development of software (new methods, community software, maturation, long-term support)

Group 5: Software

- What do you see the role of AI being in relation to astrophysics technology?
  - Industry partnership opportunity
  - Onboard processing
  - Software development, documentation, help desks
  - Calibration and science analysis (with guardrails)