Astro2010
Technology Development White Paper

Technology Investments to Meet the Needs of Astronomy at Ultraviolet Wavelengths in the 21st Century

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Introduction

Observations at ultraviolet wavelengths (~ 90-300 nm) are an integral component of the multi-wavelength approach taken in modern observational astrophysics to understand objects ranging from planetary atmospheres to the large-scale structure of the Universe. The rest-frame UV Universe is visible only by observatories in space or by sub-orbital sounding rocket payloads, except for very restricted wavelength regions accessible to high-altitude balloon experiments. Beginning in the 1970s and continuing to the present time, NASA has had a highly successful progression of missions (Copernicus, Voyager, IUE, EUVE, SOHO, HST, FUSE, GALEX) and instruments aboard the Space Shuttle (HUT, UIT, WUPPE) that have provided unique views of the UV Universe. These missions have been critical in shaping our knowledge of interstellar and intergalactic media, galaxies and galactic halos, stellar winds, stellar atmospheres and chromospheres, r- and s-process element production, the composition of interstellar dust, the Local Bubble of hot gas in which the Sun resides, the Martian atmosphere, aurorae on Jupiter and Saturn, and the composition of exoplanet atmospheres to name but a few items in a long list of phenomena explored at UV wavelengths. As the value of UV observations to astronomy has grown, so too has the need to make the observations more efficient and compatible for use in multi-wavelength studies. There are many promising technologies that could lead to significant advances in the quality of UV instrumentation. In this white paper, we outline what we consider to be the two most important areas of further research: detector development and reflective coatings for optics. Most NASA funding in these areas has occurred in the early stages of past flight programs or in the ongoing ROSES/APRA solicitations, but these efforts have been modest compared to those needed to achieve the truly revolutionary science results envisioned for the next 10-20 years from the next generation of Explorers or a large UV-optical successor to Hubble.

> *We urge the Astro2010 Committee to recommend dedicated technology investments in <u>ultraviolet detector development</u> and <u>optical coatings</u> in the next decade that will enable new Explorer-Class missions, enhance the efficiency of future Observatory-Class missions, and reduce costs associated with cutting-edge science.*

Why Investments are Needed Now

Detectors and optics are fundamental components of all instruments designed to detect electromagnetic radiation. The benefits of investing in UV detectors and higher reflectivity coatings for optics would be realized by all future missions with UV instrumentation, regardless of size. UV capabilities will be needed for general-purpose observatories (e.g., a Hubble successor such as THEIA, NWO, or ATLAST) as well as smaller specialized missions (e.g., a cosmic web probe). There are numerous examples of such missions in the Astro2010 Notices of Interest,[1] and science drivers in the Astro2010 Science White Papers.[2] Given the long development times anticipated for future large (4-16m) UVOIR space observatories, work on instrument design must begin soon if such a mission is to occur in the next decade or soon thereafter. Many of those instrument designs will rely heavily upon progress made in UV technologies, and consequently those technologies must be ready, or at least have demonstrated that they can be ready, prior to the time the instruments undergo their major design reviews.

Timely rejuvenation of the Explorer mission line will also depend on near-term technology investments.

UV Technology Investments

Appropriate investments in UV technology in the next decade could easily yield science returns at a far lower cost than the equivalent science would cost using present-day technology. Consider the following table, which compares the spectroscopic sensitivity of several telescopes using existing (Hubble) technology compared to telescopes that have been "optimized" by improving one facet of performance – in this case, system throughput.[3]   A factor of 4 improvement in throughput is equivalent to *at least* a factor of two in the size of the telescope primary mirror, possibly more depending on the source and detector background rates.   For example, an optimized 4m telescope would have the light collecting power of an 8m HST. This

Table 1: Exposure Times for Telescopes With and Without New Technology Investments					
Flux (erg cm^{-2} s^{-1} Å^{-1})	GALEX FUV (mag)	Exposure Time to Reach S/N =10 at R = 20,000			
		HST / COS	4m HST or Optimized 2m	8m HST or Optimized 4m	16m HST or Optimized 8m
1x10^{-15}	19.2	9.8 ksec	3.6 ksec	900 sec	220 sec
1x10^{-16}	21.7	115 ksec	39 ksec	9.1 ksec	2.2 ksec
1x10^{-17}	24.2	2.9 Msec	700 ksec	110 ksec	24 ksec
Calculations assume a 2-mirror OTA with 12% secondary linear obscuration, feeding a single reflection spectrograph with a detector dark count rate of 2.7x10^{-4} cnt s^{-1} per resolution element. Optimized telescope configurations assume a factor of 4 improvement in system throughput compared to existing (Hubble) technology.					

simple tabulation demonstrates that with appropriate technology investments it may be possible to achieve equivalent science performance with telescopes of reduced sizes and, by extension, dramatic cost differentials of hundreds of millions, or even billions, of dollars. To realize these science gains and cost savings, there must be 1) a disparity between present-day capability and required performance, and 2) a technological approach that will achieve the required performance. At UV wavelengths, unlike the optical or near-IR, system throughputs tend to be quite low because detector quantum efficiencies are low (often less than 30%) and grating/mirror coatings have only modest reflectivities (often less than 80%). There is plenty of throughput "headroom", and there are clear technology paths forward that will lead to dramatic throughput increases.

> *Increasing system throughput is the single most important and cost-effective way to increase science productivity at UV wavelengths.*

Table 1 shows that system throughput can be traded for aperture or integration time. It can also be traded against resolution (spatial or spectral) and optical design, particularly the number of reflections in the optical path. This latter consideration can be especially important because optical layout, packaging, and aberration control are key elements of spectrograph and camera design. A reasonable goal for increasing system throughput at wavelengths below 300 nm would be to bring the sensitivity of UV observations on par with those at optical wavelengths. This is

critical for many science areas where coverage at both UV and optical wavelengths is desirable, either spectroscopically or in imaging programs requiring optical and UV filters. It would also open up possibilities for dual-channel instrument designs that are able to take full advantage of an extension of the optical bandpass to shorter wavelengths.

Detectors

Detectors are the cornerstones of astronomical instruments. All of the effort and expense associated with placing light onto a detector is subject to the efficiency and fidelity of the photon detections at this final component in the optical path. Given the intrinsic faintness of most astronomical sources of light at UV wavelengths, imaging and spectroscopic UV instruments have used photon-counting arrays for decades. These arrays have typically had low quantum efficiencies (QEs) over large parts of the detection bandpass. For example, the Cosmic Origins Spectrograph (COS), which will be installed on Hubble during Servicing Mission 4, has a detector QE of 10-20% over much of its 120-300 nm bandpass (see Table 2).[4]

Table 2: Detector Quantum Efficiencies for HST-COS								
	CsI Photocathode + MCP						CsTe Photocathode + MAMA		
Wavelength (nm)	122	130	140	150	160	175	200	250	300
Detector QE	34%	30%	23%	20%	13%	10%	10%	9%	4%

An interesting comparison can be made between present-day UV detector and optical/IR detector technology in the 1970s and 1980s. When Hubble was designed, all wide field imaging and most spectra were obtained with photo plates (1-2% QE) and imaging photocathodes (like those on HST-FOC) rarely reached 20%. Now we have CCDs with QE > 50% over broad bands and with QE > 90% in selected wavelength regions. The growth in IR technology has been even more remarkable. Twenty years ago, the standard ground-based IR detector was an InSb 58x62 pixel device with NICMOS 256x256 devices becoming available due to HST development funding. Now, 2000x2000 pixel devices with near unity QE and very low noise are practically commercial products. Similar advances can and should be made at UV wavelengths!

Current UV detection technology can be classified into two major categories. The first group combines a photoemissive device (such as a photocathode) with a gain component [such as a microchannel plate (MCP)] and an electron detector. The second group consists of solid-state devices based on silicon [e.g., Charge Coupled Devices (CCDs) and Complementary Metal-Oxide Semiconductor (CMOS) devices] or wide bandgap semiconductor-based detectors such as GaN/AlGaN.
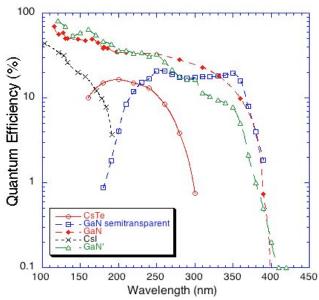
Photocathodes

Progress towards the goal of photoemissive UV detectors with high QE, low noise, and large-area formats depends strongly on the efficiency of photocathodes. This is true for MCP-based detectors as well as electron-bombarded arrays. In recent years there have been some extremely promising developments in this field, which should provide some guidance for investments in the coming decade.

GaN and its alloys, especially AlGaN, are excellent photocathode materials due to their low electron affinity, chemical stability, direct bandgap, and tailorability of response (by varying Al fraction). QEs of 70-80% at 122 nm have been measured for planar cesiated p-doped AlGaN

opaque photocathodes, with a steady decline to 10-20% near 360 nm.[5,6,7] This represents significant improvement over previous technologies using conventional CsI and CsTe photocathodes (Figure 1), but these results have not yet been realized for large-format detectors suitable for astronomical observations in a space environment. The highest QEs on windowed UV detectors to date have been achieved with planar GaN on sapphire substrates in opaque mode, with photoelectrons emitted from the same surface as the photons enter.[6] The high QEs likely result from matching the crystalline structures of the GaN and sapphire, which reduces defect traps that limit the photoelectron mean free path to exit the surface.

Cesiated photocathodes currently require sealed tubes to retain the Cs; they are limited to windowed detectors, with wavelengths above ~105 nm. The current approach to observing shorter wavelengths is to use a non-cesiated photocathode (e.g., KBr) to cover wavelengths below ~122 nm, as was done for FUSE. Non-cesiated photocathodes have the advantage of being stable and do not require a sealed tube (i.e., they can be used with windowless detectors). A possible avenue of exploration for missions that require access to the wavelength region shortward of Lyman-α is the use of structured photocathodes. Promising work has been done on demonstrating non-cesiated photocathodes using epitaxial surface bandstructure engineering.[8] Nanowires with strong internal fields might achieve negative electron affinity without cesiation, which would allow them to operate without windows and observe at shorter wavelengths; however, this has not yet been demonstrated.

Figure 1: *Quantum efficiency as a function of wavelength for several photocathodes.[6,10,11] The curves shown for CsI and CsTe photocathodes are representative of those currently available on HST at wavelengths $\lambda > 120$ nm.*

Significant improvements, such as raising QE substantially at longer UV wavelengths, should be feasible if current technology efforts are augmented. Promising approaches include the use of structurally purer AlGaN, improved p-doping profiles, and alternate materials such as MgZnO.[9] The use of GaN as a photocathode material would allow broader wavelength coverage than conventional CsI or CsTe photocathodes (Figure 1), which would obviate the need for multiple detectors to cover the 100-300 nm wavelength range, thereby simplifying instrument designs.

Considerable work needs to be done to extend these results to semi-transparent mode, or to the surfaces of MCPs to maintain opaque mode. Initial demonstrations have shown that cesiated opaque GaN cathodes can be made on normal glass MCPs and on advanced ceramic MCP

substrates.[6,11] Although these proceses appear to achieve desirable results, the efficiency and reliability of these configurations have not yet been optimized.

Microchannel Plate (MCP) Detectors

The development and performance of photon-counting detection devices based on microchannel plate technology is illustrated by their use on a variety of successful space missions for both imaging and spectroscopy (e.g., SOHO, ROSAT, HST-STIS, EUVE, CHANDRA, SAMPEX, IMAGE, FUSE, HST-ACS, TIMED, ROSETTA, CHIPS, GALEX, New Horizons P-ALICE, and soon LRO-LAMP, JUNO-UVS, and HST-COS). MCPs have a wide range of desirable attributes for flight detectors – high reliability, low power and weight, operation at room temperature, immunity to the radiation environment of space, solar blindness, high temporal resolution, and non-planar (curved) format options. For these reasons, they are likely to remain an attractive choice for future space missions requiring UV detectors.

There are significant challenges in the implementation of detectors for ambitious UV instruments on future astrophysics missions. Consider, for example, the THEIA mission.[12] The strawman concept for the THEIA UV spectrograph detector baselines a sensor scheme with a geometry similar to, but much larger than, the HST-COS far-UV MCP detector system. The COS detector active area is 179 mm long x 10 mm wide curved to a focal plane of 0.6 m radius for the Rowland circle (see Figure 2). The COS FUV detector has a spatial resolution of ~25 μm with electronic sub-resolution sampling using a cross delay line readout anode. The THEIA detector scheme will be at least twice as large and will require spatial resolution (10μm) that is more than twice as good, coupled with quantum efficiency that is significantly better at long wavelengths.

Figure 2: *HST-COS far-ultraviolet detector showing the two abutting microchannel plate detector segments (each 85 x 10 mm) curved to the focal plane of the spectrograph.*

Developmental work is needed in many areas beyond quantum efficiency and format extension. These include: the fidelity of MCP amplification, readout performance, electronics development, and noise suppression. For example, with anti-coincidence shielding, background counts in MCP based detectors can be greatly reduced,[13] although this imposes constraints on the detector design and construction. Similarly, encouraging progress is being made on reducing fixed-pattern noise introduced at the "dead zones" at the boundaries of the MCP fiber bundles
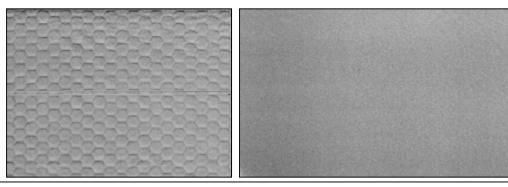
Figure 3: *(Left) HST-COS flat field image of a 10 x 13 mm area of the far-ultraviolet MCP detector.[4] The fiber bundles imprint an obvious fixed-pattern noise features in the image. (Right) A new glass process MCP flat field for a similar image area, demonstrating the absence of fixed-pattern noise.[14]*

(see Figure 3). With appropriate instrument design and detector development, true flat fields akin to those available with solid-state devices may be possible in future missions.

Advanced Electron-bombarded Arrays

Electron-bombarded arrays tailored for UV applications may offer even higher QEs. Advances in compactness, magnet-free proximity focusing, reduced weight and ease of manufacturing recently demonstrated at proof of concept[15] could make these devices more attractive for flight. Use of delta-doped CMOS arrays will enable low voltage and versatile readout.

Solid-State Devices

To date, solid-state arrays have not been featured prominently as UV flight detectors partially due to the fact that many solid-state arrays are not solar blind or because they do not offer photon-counting ability. However, new developments are making solid-state arrays viable for solar-blind UV imaging and spectroscopy applications. Substantial investments have been made in silicon visible imagers to produce detectors with very low noise, low dark current, and large (greater than 4k × 4k pixels) image formats. Silicon sensor response is being extended into the UV using delta doping[16] and AR coatings, achieving 100% internal QE in the UV and excellent external QE (e.g., 50-90% at wavelengths of 200-300 nm). Delta doping also offers highly uniform and stable response.[17,18,19] Silicon imagers are making headway into flight; for example, the 4k x 4k CCD array to be flown on HST-WFC3 has readnoise levels of <3e⁻, excellent cosmetic properties, and QEs of 30-60% between 200 and 300 nm.[20]

For applications involving moderate-high resolution spectroscopy, very low noise detectors are needed, and thus the development of large-format photon-counting CCD or CMOS systems will be extremely important. New techniques such as lateral gain CCDs, electron multiplied CCDs (EMCCDs), and low noise CMOS sensors are being developed, indicating that silicon sensors should continue to improve in viability for photon-counting applications.[21,22]

Another strong technology driver for silicon-based focal plane assemblies is the need for increased radiation tolerance, which will be crucial for future space missions with extended lifetimes. Radiation damage reduces silicon detector lifetimes and introduces time-dependent performance degradation that is difficult to calibrate (e.g., charge transfer efficiency losses, permanent hot pixels). P-channel arrays have higher radiation tolerance than n-channel devices by nearly an order of magnitude.[23,24,25] CMOS devices do not employ pixel-to-pixel charge transfer across the detector active area as CCDs do, so they are inherently more radiation tolerant. Recent radiation tests confirm low noise performance[26] and radiation hardness over 1 Mrad(Si).[27]

Recommendations

We recommend pursuing several UV detector development paths in the next decade:

- Development of GaN and GaN-alloy photocathodes, for use in both opaque and semi-transparent modes. Development of non-cesiated AlGaN photocathodes.

- Increasing QEs for large-area MCP detectors to >50% (and preferably >75%) in the 100 to 300 nm wavelength range. Such devices are envisioned for the far-UV instruments on the THEIA and ATLAST mission concepts.[12,28] Several alternative approaches appear promising:

Glass MCPs with cool deposition of AlGaN or MgZnO (normal deposition of GaN is too hot for glass MCPs to survive)

Ceramic MCPs (e.g., silicon or alumina) for hot deposition of AlGaN (silicon MCPs with AlGaN deposition are already being pursued via Small Business Innovation Research grants).

- Development of a new generation of detectors that use opaque planar photocathodes for the highest QEs, including development of magnet-free, compact electron-bombarded arrays. Currently, the only known technique to use opaque planar photocathodes is the oblique magnetically-focused electron-bombarded CCD (previously flown by IMAPS) or CMOS.

- Development of large-format (at least 8k x 8k) back-illuminated delta-doped solid-state (CCD or CMOS) photon-counting arrays for very low light applications. Such devices are envisioned for the near-UV instruments on the THEIA and ATLAST mission concepts.[12,28]

- Increasing the technology readiness levels of the next generation of UV detectors through the sub-orbital rocket and balloon programs.

Our recommendations echo those in the Ultraviolet and Visible Detectors Roadmap Report submitted by the UV-Visible Detectors Working Group of NASA's Office of Space Science in 2001.[29] See that report for additional recommendations.

Optical Coatings

Most telescopes require broadband spectral reflectance, and metal is the material of choice for such applications. Silver and gold are typical coatings for visible and infrared telescope optics, while aluminum is used for UV applications (Figure 4). At ultraviolet wavelengths, the reflectivity of optical surfaces plays a major role in the overall system throughput and optical design of instrumentation. Unlike the optical or near-IR, where there can be tens of reflections in a system without serious photon loss, reflections at UV wavelengths cost dearly. The problem is that aluminum forms a native oxide layer (Al_2O_3) that becomes highly absorptive below 200 nm and significantly degrades UV reflectivity. Some UV reflectance can be preserved by protecting bare aluminum with a fluorine material overcoat. Currently, UV instruments use the
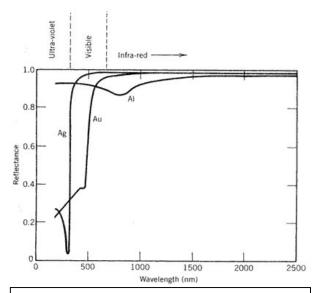

Figure 4: Reflectivity of three commonly used optical coatings: Al, Ag, and Au.[30]

native reflectivity of aluminum (>80% throughout the UV) and typically protect it from oxidation by the application of a thin layer of an impermeable material like MgF_2 (70 – 80%

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throughput down to 115 nm) or LiF (60% throughput down to 100 nm). For reference, HST uses Al+MgF$_2$ on its primary mirror, secondary mirror, and many instrument optics, while FUSE uses Al+LiF in its long wavelength (100-120 nm) channel. The other option is to use a solid crystalline material (SiC or B$_4$C down to 60 nm), although the reflectance at longer wavelengths is highly compromised and the overall reflectivity is only ~30-40%.

Presently, the number of reflections is a serious limitation for some UV instruments, particularly at wavelengths below the 115 nm MgF$_2$ cutoff.   Even modest increases in reflectivity could have major impacts on optical designs. (It would take twenty-one 95% reflections or ten 90% reflections to result in a photon loss equivalent to only three 70% reflections.)

Far ultraviolet capabilities of future Observatory-Class missions will require optical coatings to be optimized over very large bandpasses (UV-IR). New advances in coating technology derived from the semiconductor industry have opened the possibility of atomic layer deposition (ALD), which would allow the production of very thin defect-free coatings that prevent the underlying aluminum from oxidization. Figure 5 shows the throughput of a 1 nm layer of single-crystal MgF$_2$; if such layers can be deposited uniformly on large optics and are stable, they may provide an avenue for high reflectivity in the UV without compromising the performance at long wavelengths. They would also alleviate environmental concerns and handling issues associated with highly hygroscopic coatings such as LiF, which must be maintained under excellent humidity control at all times prior to launch. Humidity control and protection of large mirrors could be a major cost driver for a 4-16m telescope with an Al+LiF primary, but this would need to be quantified before rejecting LiF as an overcoat as there are good reasons to choose it based on science needs.
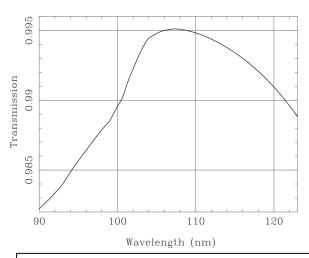

Figure 5: *Transmission as a function of wavelength for a 1 nm thick coating of MgF$_2$. ALD may be able to produce coatings that have almost no impact on the intrinsic reflectivity of the underlying aluminum. Such an optic would have reflectivity of >80% throughout the far-UV to the near-IR. This can be compared to ~60% reflectivity for Al+LiF at 100 nm.[31]*

Over the years, many different coating materials have been examined but none have been found superior to MgF$_2$ or LiF. Currently, three additional approaches are being considered: Al:LiF Alloy, Al:Ga alloy, and Al with a fluorite overcoat. NASA developed Al:LiF alloy for use on the Space Shuttle because it is less dense and stiffer than conventional aluminum. There has been anecdotal evidence that Al:LiF alloy does not form an oxide layer because the LiF captures the aluminum's free electrons; however, early tests do not appear promising. Al:Ga alloy has recently gained attention for use as a catalyst material for generating hydrogen from water because it exhibits limited oxidization.[32] Therefore, Ga and Al:Ga alloy are being investigated as potential coating materials. So far, it has been learned that gallium can be deposited over bare aluminum, but the result is an embrittled surface unsuitable for most optics.

Aluminum fluoride, AlF_3, is a well-known material currently used as a coating material for UV (157 nm and 193 nm) lithography optics. It is not affected by water and has good mechanical strength. At present, an effort is underway to develop a chemical conversion method to convert the native oxygen layer produced on bare aluminum into an ultra-thin protective AlF_3 overcoat that is dense, mechanically robust, and has minimal optical absorption. The process combines physical vapor deposition and chemical vapor deposition.[33] Physical properties, such as film thickness, are controlled by pressure, temperature, chemical species, and flow rate. The application of the process to large (4-8m) mirrors is consistent with the current state of the art. The only expected addition to current coating methods is the introduction of fluorine gas for the chemical conversion. A full coating characterization study including environmental degradation should be performed to study the efficacy of this coating.

Recommendations

We recommend pursuing several optical coating development paths in the next decade:

- Continued development of atomic layer deposition processes and testing for common coating materials such as MgF_2.

- Further research and testing of AlF_3 chemical and physical vapor deposition processes.

- Investigations into alternate coatings and technologies that may be available, or become available, through the military, semi-conductor industry, or other manufacturing sources.

- Definition and development of handling processes, contamination control, and safety procedures related to depositing coatings, storing coated optics, integrating coated optics into flight hardware, and ultimately launching these optics into space. Technology readiness levels required for flight are available for common coatings on optics sized for HST and FUSE, but scaling to larger (4-16m) telescopes will require additional investments and research.

- New coatings will need to be matured sufficiently and proven in the sub-orbital rocket or balloon programs in preparation for use in space.

Summary

We recommend that NASA continue to invest in UV technology development that leads to substantial gains in UV instrument throughput. In terms of the number of photons collected per dollar, this is an extremely cost-effective way to increase science return at UV wavelengths without requiring larger aperture telescopes. For development areas where these investments are applicable to missions of all sizes, such as detectors and optical coatings, dedicated funding beyond that available in the ROSES/APRA solicitations should be of a sufficient scale to make progress quickly so that these benefits can be realized as soon as possible in future mission designs. We estimate that this may require a total of $20M-$30M spread out over 3-5 years, perhaps more depending on how many approaches are pursued; a thorough and critical assessment of the specific technologies identified in this paper would provide guidance on the optimal path forward. Additional resources should be allocated to testing these new detectors and coatings in the sub-orbital rocket and balloon programs.

Investments in detectors and coatings will enable smaller missions by expanding their photon grasp and making them substantially more capable. For missions that combine UV capabilities

with those at other wavelengths, particularly large Observatory-Class missions, these same investments will maximize science return – either by opening previously unobservable portions of the Universe, or by increasing observing efficiency by reducing the amount of exposure time required to reach a given signal-to-noise ratio. We ask that the Astro2010 Survey Committee take these considerations into account in developing its strategy and recommendations for incorporating technology investment expenditures into its 10-15 year vision for NASA astrophysics missions.

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