Astro2020 Science White Paper

Method to aluminum-coat telescope mirrors in space for EUV-broadband astronomy

Thematic Areas: ☒ Planetary Systems ☒ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics

☒Stars and Stellar Evolution ☒Resolved Stellar Populations and their Environments

☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

Principal Author:

Name: David A. Sheikh

Institution: ZeCoat Corporation

Email: dsheikh@zecoat.com

Phone: (858) 342-7515

Co-authors: (names and institutions)

none

Abstract:

Telescope mirrors and gratings coated on-orbit with bare aluminum may allow broadband observations that include the EUV band between 30-nm and 100-nm. To date, this EUV band has been less explored because of inadequate earth-made, reflective coating technology. A telescope coated in the vacuum of space would have broadband coverage from the EUV through the long IR.

High-discharge lithium battery technology exists today to build a large, self-coating telescope in space. The Soviet Union coated an EUV telescope in space with partial success in 1975, but now the world has much better batteries, and four decades of additional spaceflight and coating experience.

Introduction

The purpose of this White Paper is to convince the reader that a telescope should be coated in the vacuum of space during the next decade. A telescope coated on-orbit with bare aluminum may allow broadband observations that include the EUV band between 30-nm and 100-nm, which to date, has been less explored because of inadequate earth-made, reflective coating technology. A telescope coated in space could have ULTRA-broadband coverage from 30-nm through the long IR.

By applying an aluminum coating in the vacuum of space, the thin oxide coating that normally forms upon exposure to earth's atmosphere, may be avoided. The thin oxide (or the protective fluoride coating typically applied to prevent oxidation) absorbs the EUV energy that otherwise would be reflected (or transmitted) by a bare aluminum reflector. By placing an EUV-reflecting iridium layer (or multilayer dielectric mirror) beneath the bare aluminum, observations may be theoretically extended to wavelengths as short as 30-nm.

Lithium battery technology developed during the past decade, makes the idea of creating a high-performance, space-based coating system, a technically reasonable endeavor. Over the past 4-years, the author has developed and demonstrated a battery-powered aluminum coating system for making ground-based aluminum films, however, this system could also produce aluminum films in the vacuum of space.

A brief history of the coating-in-space conversation

The idea of coating a mirror is space is not new. In fact, the potential benefits of coating in space have been discussed for over 50-years.

Here is a brief historical timeline of noteworthy coating-in-space events:

1967 – Hass et. al. suggested an iridium reflector overcoated with bare aluminum in-space could widen the broadband reflective response of an aluminum film from about 85-nm, deep into the EUV down to about 50-nm [Ref. 1]. More recent calculations indicate the lower limit may be closer to 30-nm. Hass wrote;

> *"The most likely application of iridium-aluminum reflecting coatings is in high resolution satellite spectrographs for studying the emission lines of stars and of the sun. In order to utilize fully their high reflectance in such satellite experiments, the aluminum film*

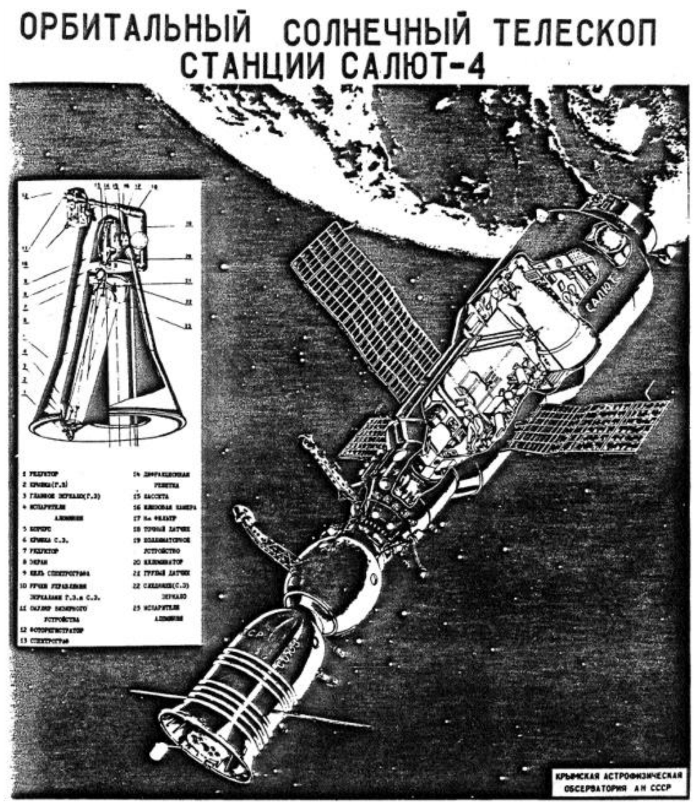

Figure 1. In 1975, Russian cosmonauts applied bare aluminum coatings to the Orbiting Solar Telescope (OST) on the Salut-4 Space Station using the vacuum of space.

has to be deposited after the satellite has been placed in an orbit high enough to eliminate surface oxidation."

1975 – Russian cosmonauts on board the Soviet Salut-4 space station coated the Orbiting Solar Telescope (OST) with bare aluminum (placed on top of a gold/zinc sulfide/germanium-multilayer). The mission was partially successful as the telescope was coated in the vacuum of space and the telescope functioned properly for a short time. However, outgassing from the spacecraft and its placement in a low-altitude orbit (340-km) caused the mirror to become contaminated by oxygen (or other outgassing components from the spacecraft), and the vacuum-UV reflectance quickly degraded [Ref 2].

Now, more than 44-years later, this feat has not been duplicated.

1983 – NASA commissions Perkin-Elmer Corporation Space Science Division to assemble a report detailing the technical issues and potential benefits of coating in space [Ref.2, click link to view]. The 173 page report concludes with the following powerful statement;

"In all likelihood, the coating of large optics in space ***is*** *the approach that will in fact be taken for the next generation of large space telescopes in the twenty-first century. The technology exists to develop this approach today."*

Now it is 2019 and 36-years later, and with the invention of lithium batteries with incredible discharge capability, it is even more feasible to coat large mirrors in the vacuum of space!

1993 – The wake-shield facility (WSF) was an experimental science platform that was placed in orbit by the space shuttle. It was a 3.7-meter diameter, free-flying stainless steel disk. The WSF was deployed three times during the mid-90's at an altitude of about 300 kilometers. The forward edge of the WSF disk redirected atmospheric and other particles around the sides, leaving an "ultra-vacuum" in its wake. The resulting vacuum was used to study semiconductor film growth in space.

Figure 2. Deployment of the WSF using the Space Shuttle robotic arm.

Pre-flight calculations suggested that the pressure on the wake-side could be decreased by some six orders of magnitude over the ambient pressure in low Earth orbit (from 10^{-8} to 10^{-14} Torr). However, analysis of the pressure and temperature data gathered from two flights concluded that the decrease was only some 2 orders of magnitude, or about 1^{-10} torr (4 orders of magnitude less than expected). [Ref. 3].

2004 - Calculations performed by Johns Hopkins University researchers for the Far Ultraviolet Spectroscopic Explorer (FUSE) program, suggested that telescope mirrors protected by a wake shield, or coating in a high-orbit such as L2, may remain uncontaminated for many years [Ref. 4].

The researchers stated;

"A careful analysis suggests that if a telescope is protected from the ram direction by placing it in the wake of a large shield, an Al coating could be used in a 300 km low-earth orbit for as long as 20 years. Such a system has significant operational constraints, because it would be necessary to adjust the spacecraft and its shield

continuously around each orbit. However, at high-earth orbit or at L2, attack by atmospheric atomic oxygen becomes moot and this approach is more attractive. In these limiting regimes, spacecraft outgassing becomes the dominant source of oxygen and the use of ultra-high vacuum materials and techniques when assembling the telescope would be requirement as would the means for recoating following an unforeseen degradation."

However, the Wakeshield Facility described in the previous paragraphs concluded a vacuum of only about 10^{-10} torr was actually experienced behind the shield, and this vacuum is not good enough to prevent coating oxidation for 20-years. Higher orbits such as L2 would likely be required for long missions.

These JHU researchers concluded with this statement;

"Use of Al as a space-based mirror requires that the coating process be carried out in orbit and that it be protected from interacting with oxygen afterward, a daunting task. However, if the space-based coating technology was mastered the reward would be an increase in throughput for a 3-reflection optical system by an order of magnitude, i.e. a COS-like effective area for a 2.4 m class instrument in the FUV."

2014- ZeCoat Corporation demonstrates a battery-powered coating process for making bare aluminum films [Ref. 5]. In 2018, ZeCoat was awarded a NASA APRA grant to use the battery-powered coating technology to develop a ground-based aluminum coating system to apply fluoride-protected, FUV-broadband coatings to large mirrors (2 to 6-meters in diameter). This work is currently in progress in support of two NASA flagship concept missions, HabEx and LUVOIR.

Battery-powered coatings – how they work and why they will work in space

A tungsten filament pre-wet with aluminum can be rapidly heated by electrical resistance to cause the aluminum to evaporate. This simple aluminum evaporation process has been around for about 100-years. Because the aluminum is held on the filament by surface tension, the process will work in a micro-gravity environment. Russian cosmonauts used this process to coat the Optical Solar Telescope (OST). Figure 3 shows a sketch of the OST telescope primary mirror with integrated aluminum evaporation system. It is likely that the two aluminum evaporators shown in the figure were powered by a large battery on board the Salut-4 space station.

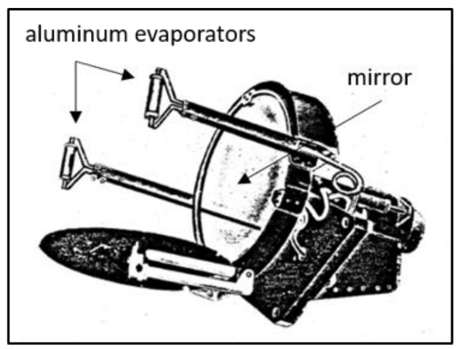

Figure 3. Russian-made OST primary mirror with integrated aluminum coating system flown in 1975

However, the OST telescope was relatively small (less than 1-m primary) and therefore required only a few evaporators and a relatively small amount of electrical power. For a future large mirror made to state-of-the-art reflectance and wavefront requirements, many evaporators and a lot of power are needed (perhaps as much as a half megawatt for a few seconds for a large mirror several meters in diameter!).

Using 2019, modern battery technology, multiple evaporation filaments powered by small lithium batteries contained in individual pressurized vessels could be placed into an array to coat a large mirror. By placing the power supply (the battery) very near each evaporation filament, electrical losses are minimized, and a tremendous amount of energy can be released very rapidly.

The batteries may be charged slowly with a solar voltaic panel attached to the spacecraft. For illustrative purposes, figure 4 shows a simple concept for coating a telescope with an array of battery-powered filaments. The reader can imagine many more realistic, complex, yet technically trivial, telescope and array deployment designs.

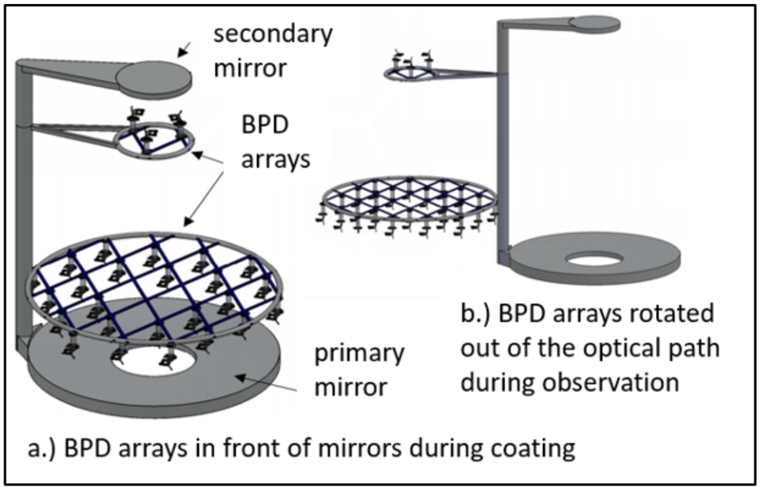

Figure 4. Sketch of how a large battery-power deposition (BPD) array might be deployed for coating and for observations

Figure 5. First proof-of-concept, battery-powered deposition system (system with filament (left), 26650 lithium batteries (middle), energized in coating chamber (right)

In 2014, the author built and demonstrated an aluminum evaporation system using a relatively crude battery-powered device (figure 5), which discharged at about 90-amps. Our latest device contains electronics to precisely control the power to the filament and small state-of-the art LiFePO4 batteries with graphene electrodes, which can discharge at 300 amps!

Driven by the cell phone, automotive, and model aircraft industries, battery technology is advancing at an almost alarming rate. During the next decade, this "Moore's Law-like" trend for battery technology will undoubtably continue, which will further reduce the mass and volume of a future space-based coating system.

Benefit to astronomy

Over the past 60-years, fluoride-protected aluminum coatings have been the standard for FUV astronomy. However, after decades of research, FUV reflectance improvement is now offering diminishing returns, while fluoride-protected coating technology is simply a dead-end for EUV astronomy (lower limit is about 90-nm). To push deeper into the EUV, past these limits, a new approach is needed for broadband coatings.

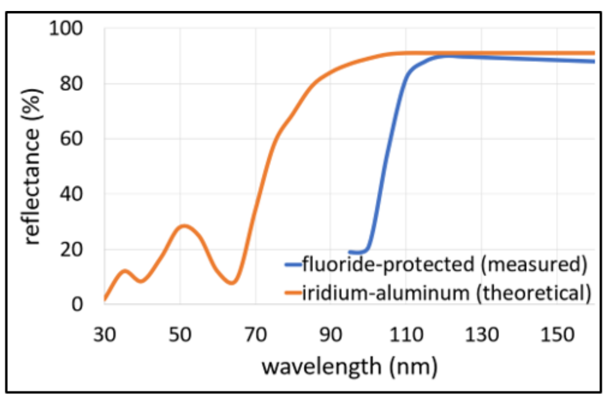

Figure 6. Theoretical reflectance of bare aluminum over an iridium reflector, compared to state-of-the-art fluoride-protected aluminum made on earth (at GSFC).

The benefits of a telescope coated in

space to astronomy would be enormous. The EUV band between 30-nm and 90-nm is rich in spectral information. Figure 7 shows some absorption bands for this region.

D. Allred suggested the concept of looking in the EUV for ionized helium trapped within the magnetosphere of extra-solar planets [Ref. 6]. This is an interesting concept because the light would be emitted directly from the planet's ionosphere (only slightly polarized), rather than solar blackbody radiation *reflected* from the planet (more polarized). Reflected solar energy is subject to polarization aberration upon interaction with coatings and gratings within the telescope, seriously restricting the telescope's design if the *coatings* are significantly polarizing (which they are). However, these detailed discussions shall be left for others more acquainted with telescope-design, chronographs, star-shades, and polarization effects.

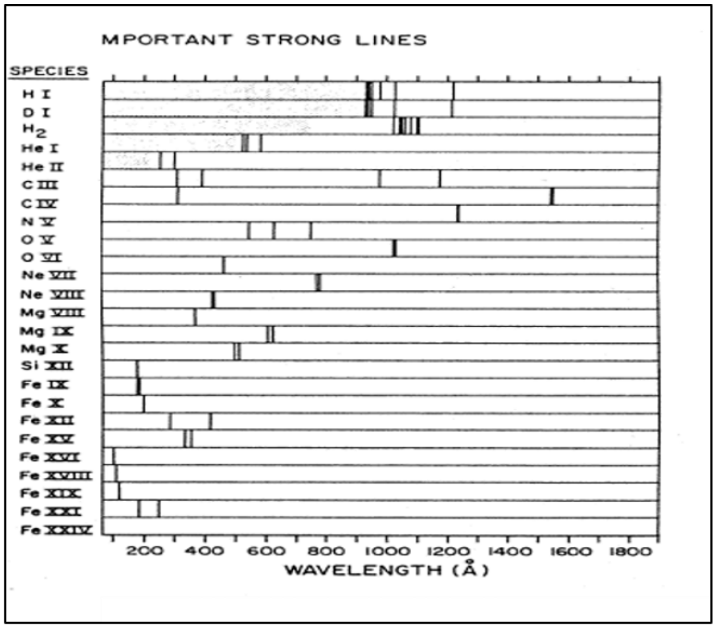

Figure 7. Absorption bands in the vacuum UV [Ref. 2]

Conclusion

The battery technology exists today to build a large, self-coating telescope in space. However, without a recommendation from Decadal committee to NASA to pursue such a mission, this development may be delayed for another ten years. I sincerely believe it would be a great pity if this astronomy opportunity were overlooked, when the key component to realize the in-space coating system is here today (modern lithium batteries). Russia tried this in 1975, but now the world has much better batteries, and much more experience.

References

[1] G. Haas, W. R. Hunter, **"**Calculated Reflectance of Aluminum-Overcoated Iridium in the Vacuum Ultraviolet from 500 A to 2000 A**",** APPLIED OPTICS / Vol. 6, No. 12 / December 1967

[2] A.N. Bunner, "Optical Coating in Space Final Report", Perkin-Elmer Corp. Space Science Division, Danbury, CT, USA, NASA-CR-175441, NAS 1.26:175441, ER-591, REPT-2983-81 (Oct. 27, 1983) Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19840013222.pdf

[3] Strozier, J.A; Sterling, M; Schultz, J.A; Ignatiev, A (2001), "Wake vacuum measurement and analysis for the wake shield facility free flying platform", Vacuum, **64** (2): 119–144, doi:10.1016/S0042-207X(01)00383-9

[4] H. W. Moos; Stephan R. McCandliss; Jeffrey W. Kruk; FUSE: lessons learned for future FUV missions. Proc. SPIE 5488, UV and Gamma-Ray Space Telescope Systems, 1 (October 11, 2004); doi:10.1117/12.550085.

[5] Sheikh, D., "Battery-powered thin film deposition process for coating telescope mirrors in space", SPIE Proceeding 9904-253, 2016

[6] D. Allred, "Understanding the degradation mechanisms of bare aluminum mirrors via VUV and EUV reflectance." NASA Mirror Tech Days Conference, (2016).