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Technical overview of the Ariel Space Telescope

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Abstract. The Atmospheric Remote-Sensing Infrared Exoplanet Large Survey (Ariel) is the M4 mission adopted by ESA's Cosmic Vision program. Its launch is scheduled for 2029. The mission's purpose is to study exoplanetary atmospheres on a target of ∼ 1000 exoplanets. Ariel's scientific payload consists of an off-axis, unobscured Cassegrain telescope. The light will be collected in photometry and spectroscopy with wavebands between 0.5 μm and 7.8 μm. The telescope consists of a primary parabolic mirror with dimensions of 1,2 x 0,7 m, all in bare Al6061. The greatest challenge is to develop the manufacturing processes to be applied to aluminum mirrors. This paper aims to overview the main processes involved in Ariel's mirrors.

Key words. space telescope, Ariel mission, aluminum mirror, bare aluminum, Al6061.

1. Introduction

Since the confirmation of the discovery of the first exoplanet on October 6, 1995, 51 Peg b (Mayor & Queloz (1995)), exoplanetary science has made giant strides, to the point of becoming a highly respected branch of astrophysics. The first planets were identified through the method of radial velocity variation, which had limitations. In fact, since the host star is much larger than a planet, the variation in its velocity is a minimal value to obtain, so they be used to identify principally the giant planets (comparable with Jupiter) and extremely close to the host star (orbits similar to Mercury) to maximize the gravitational interaction and increase the radial velocity variation. With technological progress, we have moved on to the detection of exoplanets through the primary transit method in which the planet, when its orbit passes in front of the parent star from our point of view, periodically reduces its brightness (see Fig. 2). Several telescopes, which had been built for other purposes, were redirected towards these studies (e.g., Spitzer), and the results were so good as to convince ESA to finance, through the Cosmic Vision Program, a whole series of missions aimed at detecting the exoplanet and study their atmospheres (Cheops, Plato, Ariel). Ariel will study the exoplanetary atmospheres of a target of approximately 1000 exoplanets. The chosen planets will be both gaseous and rocky, with a temperature between 300 and 3000 K, and which orbit around stars from A to M. To obtain the atmospheres, Ariel will study the secondary transits by analyzing the absorption lines of the starlight reflected by the

Fig. 1. Artistic picture of Ariel.Credit: European Space Agency (ESA), Science and Technology Facilities Council Rutherford Appleton Laboratory, University College London, Europlanet-Science Office.

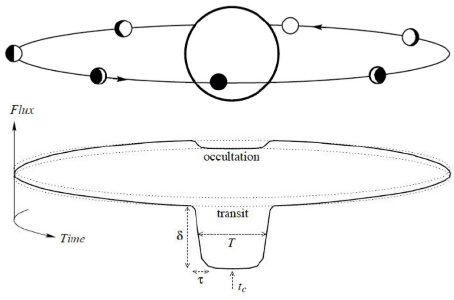

Fig. 2. Representation of transit and occultation and flow variation over time due to these phenomena (Winn (2010)).

planet's atmosphere (see Fig. 2), and it will be the first telescope designed and built for this purpose. Its mission will last approximately four years, extendable up to six. It will be positioned at the Lagrangian point L2, an unstable equilibrium point such that, once a low-mass object is placed, it will not be affected by the gravitational effects of two large-mass objects close to it. The L2 point is located beyond the imaginary line that joins the Sun and the Earth. Positioning a telescope in L2 means covering solar infrared (IR) emissions with the Earth, and the distance from the latter allows the terrestrial IR emission to be minimized (see Table 1). The mission includes a survey period where the spectra of ~1000 exoplanets will be observed to understand how many planets have clouds in their atmosphere, how many small planets still have H/He, obtain color diagrams, and improve the values of the orbital parameters in visible and IR. After this phase, a deep survey of approximately 500 targets will be carried out to identify the atmospheric compositions and thermal structure. Finally, between 50 and 100 exoplanets will be identified to study their atmospheric circulation and spatial and temporal variability. To do this, the telescope will observe in a frequency range ranging from 0.5 to 7.8 μm simultaneously in photometry and spectroscopy. The mirrors and the structure of the optical bench will be entirely made of Al6061T651 alloy aluminum.

2. Project organization

The satellite will be created through a consortium of ESA, the individual research institutes of ESA's 17 European member states, the Japanese Space Agency (JAXA), the Canadian Space Agency (CSA), and NASA (see Fig. 3).

The leading Italian contribution concerns the creation of the satellite telescope. Furthermore, on the Italian territory, we can boast private companies; first of all, Media Lario S.r.l[1], which will develop the process to create the mirrors, and Leonardo S.p.A.[2] for constructing the structure.

The telescope consists of a primary (M1) parabolic mirror with dimensions of 1,2 x 0,7 m, followed by a hyperbolic secondary (M2), a parabolic collimating tertiary (M3), and a flat-folding mirror (M4), all in bare Al6061. The telescope mount will be an off-axis Cassegrain, so the primary shape will be an ellipsoid, and the surface will be parabolic (see Fig.4).

[1] https://www.medialario.com/
[2] https://www.leonardo.com/it/home

Table 1. Main characteristic of the Ariel space mission.

Elliptical Primary Mirror	1.2 x 0.7 m
Mission Lifetime	4 Years
Payload Mass	~ 300 kg
Dry mass	~ 950 kg
Launch Mass	~ 1200kg
Destination	L2
Launch Vehicle	Ariane 6-2

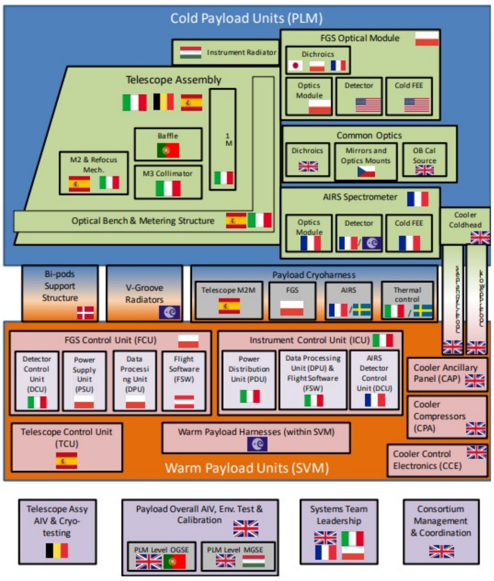

Fig. 3. Ariel Payload architecture and responsibilities (Ariel Consortium Team (2020)).

3. Process development plan for aluminum mirrors

The choice of mirror material fell after a trade-off in phase 0 of the project between different possible materials on Al6061T651 aluminum. This choice was dictated by the need to maximize the heat exchange between the primary mirror and the optical bench (as the mirror will have to reach a temperature of 55 K) and add a degree of innovation to the project (see Table 2).

3.1. Risks detected for aluminium

Until now, an aluminum mirror the size of Ariel's primary had never been created for space; it was necessary to understand all the critical issues of the material and develop the thermal and mechanical processes from scratch to make it usable. The main risks identified were two: - Its low density (three times lower than commonly used materials) makes mirror polishing of the optical surface difficult. Normal polishing processes resulted in deep scratches and a widespread opacity over the entire surface. - Its elasticity under mechanical stress. Aluminum absorbs the mechanical stress it receives during the various processes (rough machining, diamond turning, and polishing) and in launch phases (10 g) and tends to release it over time, risking adding a shape error in the primary mirror during of flight, thus rendering the telescope unusable.

To resolve these risks, we developed every single process for creating IR optics from scratch, tailoring it for aluminum.

A series of test samples were created, ranging from the actual size of the primary mirror (called Pathfinder Mirror) to disks of 50 mm in size (see Fig. 5). They were used to test different heat treatments, diamond turning, and polishing recipes.

3.2. Heat treatment

Heat treatment is a process of tempering the material necessary to allow it to harden and become elastic enough to immediately release the

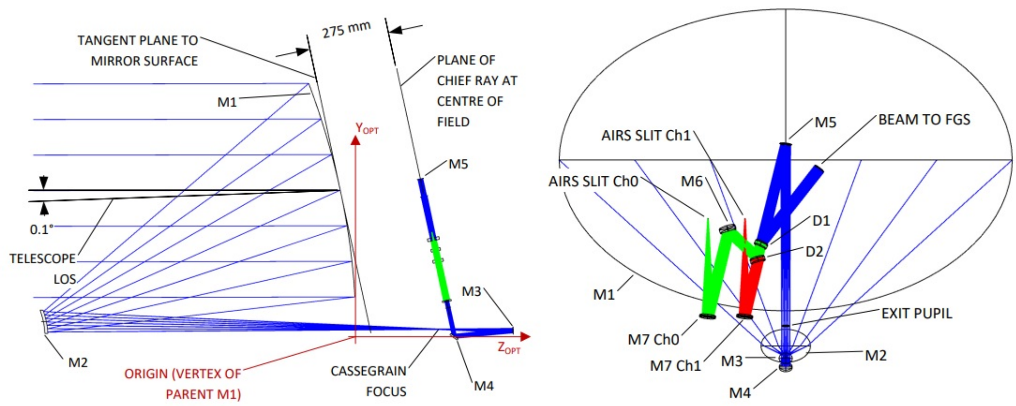

Fig. 4. Scale drawings of the telescope and common optics. On the left is a view in the Y_{OPT}-Z_{OPT} plane. The 0.1° offset is exaggerated for clarity. At right is a view in X_{OPT}-Y_{OPT} plane (Ariel Consortium Team (2020)).

Table 2. Materials for IR mirrors, pros and cons.

Materials	Pro	Cons
Aluminum alloy	Mounted on an optical bench of the same material it automatically compensates the temperature	It is necessary to develop the polishing process, heat treatment, diamond turning process etc.
Ceramic glass or Zerodur®	Easy to polish	Difficult to assemble
Silicon Carbide	Low CTE, high hardness, rigidity, and thermal conductivity	Releases humidity
Beryllium	45% lighter than aluminum and 5 times stiffer	Toxic, difficult to work with and expensive

mechanical stress it receives; for mirrors operating in the IR, cold cycles alternate at the mechanical process with cryogenic temperatures. In the case of aluminum, which is ductile and malleable, it was necessary to carry out a hot pre-treatment to relax the material thoroughly and dissolve the Si-Mg aggregates, which also affected polishing (making the piece opaque). These hot cycles reached temperatures close to those of aluminum melting. Subsequently, the aluminum was cold-cycled after each mechanical processing to increase its elasticity and quickly release stress (Guerriero et al. (2022)). This process should ensure that the piece keeps its shape the same once it arrives at L2.

3.3. Polishing

The primary mirror requires a roughness of less than 10 nm Root Mean Square (RMS) and a shape error of less than 60 nm RMS. The values are moderate, but for aluminum, it is necessary to develop the process by varying the different polishing parameters (through a DOE Design of Experiment). These tests were carried out at Media Lario S.r.l. and required two years of work. To resolve the problem of deep

Fig. 5. On the left is the image of the PTM together with 150 mm diameter samples inside an oven to carry out a hot thermal treatment, and on the right is the image of the 0.7 m diameter BreadBoard mirror after having carried out a diamond turning.

scratches and diffuse haze, a recipe was developed that requires an extremely fine slurry grain combination to remove the material delicately, low pressure so as not to deform the mirror, and, consequently, an extremely long processing time (about 16 hours).

3.4. Diamond turning

The only risk encountered for diamond turning was not having a machine large enough to machine a mirror with dimensions more significant than one meter. Currently, the German company LTUltra[3] is building and testing a new machine for the Ariel Project.

4. Conclusions and next steps

The project is preparing to reach phase C, where the telescope's design will be blocked (Critical Design Review). The last activity to be carried out will be to insert a physical stop in front of the primary mirror in the drawing to reduce the stray-light effect. Once this is done, the design will be frozen, and we will move on to creating the flight prototype mirrors and carry out the usual tests to validate them for space.

[3] https://www.lt-ultra.com/

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