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Ariel Space Telescope: Innovation for the new optics

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Summary. — Atmospheric Remote-Sensing Infrared Exoplanet Large-survey (Ariel) is a visible/infrared mission funded by the European Space Agency. It will be launched in 2029 and will aim to observe a target of ∼1000 exoplanets to study their atmospheres in chemical composition and ephemeris. Ariel will be the first space mission designed specifically for this purpose. The intervention aims to give an overview of the space project; in particular, the Italian contribution to the realization of the telescope will be emphasized. The telescope will be an off-axis Cassegrain with an elliptical-shaped parabolic primary mirror of considerable size (1.1×0.7 m optical area) entirely made of bare aluminum. Today, an aluminum mirror of this size (mainly for its major axis) has never been created for infrared observations. For this reason, the Italian team, supported by the industry, has planned a development, qualification, and validation campaign for a series of manufacturing processes for these optics. In particular, it will illustrate how the development of heat treatment, diamond turning, polishing, and coating were addressed to obtain large-sized polished aluminum optics.

1. – Introduction

The discovery of the first planet orbiting around a star other than our Sun, which occurred in October 1995 [1], opened Pandora's box on new possibilities for searching for such objects, renamed "exoplanets" (where the prefix exo- $\varepsilon\xi\omega$ from Greek means "outside" to underline its being a planet outside the solar system), to the point of creating over time a new branch of astrophysics that we call exoplanetary.

This branch initially concentrated on developing techniques to identify exoplanets, using interactions with their much more visible parent stars, seeing the periodic variations in their physical characteristics, such as radial velocity initially and then brightness. In particular, implementing the technique of measuring variation in brightness through the occultation method (see fig. 1) has made it possible to identify an ever-increasing number of exoplanets with the most disparate characteristics. The occultatio method identifies an exoplanet that follows an orbit that lies in a plane parallel to the direction of view of our detection instruments and exploits the fact that the exoplanet, during its orbital

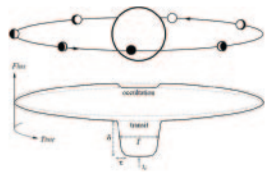

Fig. 1. – Representation of transit and occultation and flow variation over time due to these phenomena [2].

period, passes in front of the parent star momentarily reducing its brightness by a small fraction (through the primary transit called primary, see fig. 1).

In recent years, this technique has also allowed us to reveal not only the presence of an exoplanet but also to extrapolate its electromagnetic spectrum using the passage of the exoplanet behind the star this time (secondary transit, see fig. 1). In fact, in that phase, just before passing behind the star, the exoplanet is totally illuminated by starlight, which its atmosphere partly reflects and partly absorbs and re-emits. Therefore, by subtracting the light that reaches us in this pre-occultation phase from that of secondary transit, of which we only have the stellar light, we will obtain the light of the exoplanet alone from which to obtain the spectrum and, therefore, the composition of its outermost layers (the atmosphere). To perform these studies in recent years, telescopes have been used which, however, were not built for this purpose (one example being the Spitzer Space Telescope). Therefore, a telescope was needed to study exoplanetary atmospheres specifically to understand also their atmospheric circulations (ephemerites).

For this purpose, the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey (Ariel) is being designed (see fig. 2). It will be a space mission equipped with a telescope and detectors that will go to the L2 Lagrangian point. This unstable equilibrium point will allow the telescope to be shielded from the Earth from sunlight, significantly reducing its noise. The telescope will work at cryogenic temperatures —about 55K— and will observe in the infrared (IR) and visible (VIS) —range from 0.5 to 7.9 microns— this is to maximize the signal from the exoplanet, which usually has its blackbody peak in the IR, and to exclude effects of brightness variation related to stellar activity in the VIS.

Ariel aims to study a target of $\sim$1000 already known exoplanets with temperatures between 300 K and 3000 K that orbit different types of stars. Of these exoplanets, in the first survey, the fraction of clouds present will be measured, the H/He ratio (which defines the primordiality of an atmosphere); in the second survey, 500 exoplanets will be selected to be reobserved to study the elemental chemical composition, the thermal

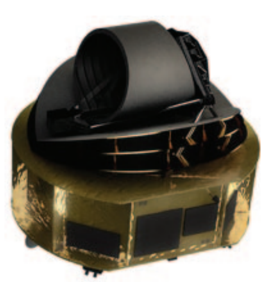

Fig. 2. – Artistic picture of Ariel. Credit: European Space Agency (ESA), Science and Technology Facilities Council Rutherford Appleton Laboratory, University College London, Europlanet-Science Office.

structure and the characterization of the clouds; finally in the third survey between 50 and 100 exoplanets will be selected to study their atmospheric circulation.

2. – Features of the Ariel telescope

The satellite is a collaboration between various European, English, Canadian, Japanese, and US research bodies led by the ESA and will be launched in 2029.

To realize this mission, Italy has a crucial role: the design and construction of the telescope.

The Ariel telescope will be an off-axis Cassegrain composed of a primary mirror M1 with a paraboloid optical surface and elliptical shape of considerable dimensions (1.2×0.7 m), a secondary hyperbolic M2, a tertiary collimator M3 parabolic and finally a flat mirror M4 to direct the light towards the instruments [3,4] (see fig. 3). Mirrors and optical bench will be entirely made of aluminum. It is essential to underline that mirrors the size of the M1, especially for its major axis, have never been made for the space in aluminum, and therefore, all the optical manufacturing processes have been from scratch.

For M1, it is required that its Surface Error (SFE) is less than 60 nm root mean square (RMS) and that its Roughness (Sq) is less than 10 nm RMS, values which are usually not difficult to achieve but which for aluminum, which is, on average three times less dense than the usual materials (NiP, Zerodur, Berillium) prove to be a real challenge.

It was decided to make the optics in aluminum after having performed a trade-off between the other available materials by evaluating the pros and cons, also taking into consideration the dimensions of the primary and the characteristics of the optical surface. Ultimately, it was chosen for the advantages of thermomechanical compensation with the optical bench, which makes the whole structure more stable, and for the potential savings that could be obtained for future missions.

The Italian team, composed of the National Institute of Astrophysics, the Sapienza University of Rome, and the National Research Center, has collaborated and collaborates in parallel with Italian companies recognized as leaders in their sector as the Leonardo S.p.a. and the Media Lario S.r.l., to jointly carry out tests on the mirrors, create the components and carry out process development.

In the following section, I will cover the more delicate processes, the risks of each identified during the development phases, and how we attempted to minimize them.

3. – Process development

The design of a mirror telescope that is intended for space or use on the ground requires, for its realization, the passage through several processes briefly explained below.

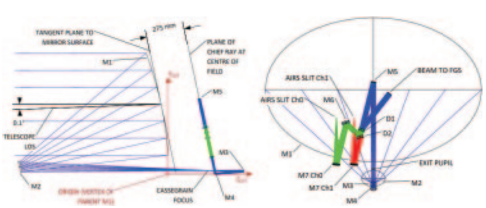

Fig. 3. – Scale drawings of the telescope and common optics. On the left is a view in the Y_{OPT}-Z_{OPT} plane. The 0.1° offset is exaggerated for clarity. On the right is a view in X_{OPT}-Y_{OPT} plane [3,4].

- Rough Machining: an aggressive mechanical process that gives the first rough shape from the raw material. The back of the mirror is also lightened through triangular holes. Usually, μm or mm of excess material are kept compared to the ideal optical surface to carry out precision machining subsequently.

- Heat Treatment (HT): composed of a series of thermal cycles, both hot to internally relax the material's structure and homogenize the alloys and cold to release the internal stresses accumulated during mechanical processing and temper the material.

- Diamond Turning (DT): once the mirror has been stabilized through the first thermal cycles, we move on to a more precise process that removes material on the optical surface. After this processing, the mirror reaches SFE$<1\,\mu$m values to peak to valley (PtV) and of Sq$\sim$7 nm RMS. The surface with these values is sufficiently reflective and homogeneous to be measured with an interferometer to obtain a map of the points to use high-precision machines.

- Polishing: very high precision processing, performed through a series of Runs in which we alternate the interferometric measurements, generating maps of the processing points. It can machine SFE$<$5 nm RMS for the hardest materials and SFE $\sim$100 nm RMS for the softest ones (such as aluminum) and bring the Sq $\sim$3 nm RMS for hard materials. However, this process deteriorates the roughness of less dense materials like ours.

- Coating: it is a layer of material vaporized on the optical surface that can be used for two purposes. The first is to create an optical processing base for polishing processing. In this case, several μm of the harder material is deposited so that processing is facilitated (for example, on the optics components, it is possible to deposit a layer often of NiP on the aluminum to polish up to Sq $\sim$1 nm RMS and SFE$<$30 nm RMS). Or deposit a much thinner layer ($\sim$100 nm) on the optical surface already machined with the polishing process and within the tolerance values, and in this case, it is used to increase the reflectivity of the surface in the Blue Bands in the VIS, this second option can be used on a bare surface (as in the case of Ariel) or on surfaces with already a thick coating.

In processing Ariel's optics, each process presents critical issues because a primary of such dimensions (1.2×0.7 m) and with such a complicated shape to work with (ellipse with the parabolic surface) has never been made until now with such a soft material as aluminum. Therefore, through a campaign production of models and samples, the risks of the individual processes were identified, and new production processes were developed.

3·1. *Rough machining.* – Phase 0 of the project (the feasibility phase) was closely linked to the ability to produce a mirror prototype from a large block of aluminum that could be created with the lightening in a triangle pattern (see fig. 4) and with a draft shape of the surface. The only critical issues in this process were finding turning machines large enough to accommodate the block of raw aluminum and ensuring the material would not crack or deform while lightening the rear. The test M1 mirror, PTM (see fig. 4), was successfully created in 2017 without showing any other critical issues.

Fig. 4. – (Left) Photo of the back of the Engineering Model (EM) mirror which shows the triangular pattern lightening. (Center) Photo of the Pathfinder Mirror (PTM) together with 150 mm diameter samples inside an oven to carry out a hot thermal treatment. (Right) Photo of the 0.7 m diameter mirror after having carried out a diamond turning. Credit: Italian Telescope Assembly Team.

3·2. *Heat treatment*. – Aluminum is a not very dense material (2.71 g/cm^3), and this characteristic generates two critical issues related to HT. The first is that any mechanical processing causes mechanical stress to accumulate inside the piece, deforming it. These stresses are not stable, and in a space environment (0 g and 55 K), they will be released, deforming the optical surface and bringing its values outside of the tolerance, which we remember to be quite stringent (SFE $<$ 60 nm RMS and Sq $<$ 10 nm RMS). The other critical issue comes from how the aluminum block was made; in our case, the lamination was the only possible process to create a dimension of 1.2 m. The lamination generates large blocks which, however, cool down on the inside more slowly than on the outside; this allows the elements of the alloy dissolved inside to reorganize themselves into crystals, which end up being torn during the surface polishing phase, generating holes in the order of the micron, bringing the roughness well out of specification. To mitigate these problems, a series of initially hot cycles close to the melting temperature of the block were developed to redissolve the aggregates (in silicon and magnesium Si-Mg), and then a series of cryogenic cycles between one mechanical process and another to release the accumulated processing stress each time and above all to temper the aluminum so that it becomes elastic enough to accumulate it no longer. Several flat samples of 150 mm [5] and a flat mirror of 0.7 m diameter were used to verify the process (see fig. 4).

The developed process gave excellent processing stability results, and the number of aggregates appeared reduced during the polishing process, observing fewer surface holes and reduced size.

3·3. *Diamond Turning*. – The only critical issue for this process was the lack of a machine large enough to machine Ariel's M1 with the Single Point DT (SPDT)(with a diamond tip) technique. The first tests were done with the Fly cutting DT (disc with a diamond edge) on the PTM, but the results were poor. Whereas the results of applying the SPDT on the 0.7 m circular mirror were excellent, and it was decided to create an SPDT machine capable of processing mirrors up to 1.2 m. It is currently under construction and will be tested in September 2024.

3·4. *Polishing*. – As mentioned in the previous paragraph, one of the critical issues encountered during polishing was the aggregates that were torn away, leaving holes; these holes make the optical surface so opaque that it brings Sq$\sim$100 nm RMS; this critical issue was, however, mitigated with the HT. At the same time, a further problem is the orange peel effect on the surface. Polishing consists of an arm with a rotating head (bonnet) in which a polishing cloth is placed, which passes over the optical surface and is polished with an abrasive slurry. Aluminum is so soft that the bonnet curls the surface when rotated, creating this effect. The only solution found to mitigate this problem was to search for the most delicate but effective parameters to polish the mirror, bringing the single run to dozens of hours of processing.

3˙5. *Coating.* – For Ariel, it was not possible to perform a thick and hard coating because, operating at 55 K, to perform IR measurements, the difference in coefficient of thermal expansion (CTE) between aluminum and hard coating could delaminate the mirror (we are, however, carrying out tests in this regard). It was, therefore, decided to apply only a thin silver coating to improve optical performance. Since this coating was only validated on the ground and not for space use, small flat samples of 10 mm diameter were made, and cryogenics and humidity tests were carried out. The samples showed no delamination, and the process was re-run on the PTM, which in the meantime was also machined applying all the processes, and also, in that case, no delamination was seen. The process was, therefore, successfully validated.

4. – Results and conclusions

This phase of process development and risk mitigation is nearing its conclusion. The latest test mirrors (the Structural Model and the EM) have been created and tested where all the knowledge accumulated in the development phase will be applied. They will soon be tested for space conditions and vibrations due to the launch. The success of these tests will allow the validation of the aluminum mirrors for space, freezing the project's design and starting the production phase of the optics for the prototype of the complete telescope.

To conclude, the manufacturing of the Ariel telescope was and still is very complex because it is a brand new project without a strong heritage, and therefore, it was necessary to undertake an intense research and development activity, which, however, is bringing good results. All this knowledge acquired can be used as a solid basis to create other telescopes of this type, ensuring good instruments with excellent heat exchange, at a low price and lightweight, all positive factors about space missions.

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REFERENCES

[1] Major M. and Queloz D., *Nature*, **378** (1995) 355.
[2] Winn J. N., *Exoplanet Transits and Occultations*, in *Exoplanets*, edited by Seager S., 2010, pp. 55–77.
[3] Ariel Consortium Team, *Ariel Definition Study Report (Redbook)*, ESA website.
[4] Ariel Consortium Team, *Ariel Assessment Study Report (Yellowbook)* ESA website.
[5] Guerriero E., Chioetto P., Tozzi A. *et al.*, *Heat treatment procedure of the aluminium 6061-T651 for the Ariel telescope mirrors*, in *Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*, Vol. **12180** (SPIE) 2022.