Consolidation of surface charging analyses on the Ariel Payload dielectrics in the early transfer orbit and L2 space environments

M. Focardi[a,b], M. Michelagnoli[b], M. Pudney[c], I. Renouf[c], P. Merola[a,*], L. Carbonaro[a], V. Noce[a], M. Vela Nunez[a], P. Bolli[a], R. Nesti[a], S. Chiarucci[a], G. Dinuzzi[a,d], E. Tommasi[e], F. De Persio[e], M. Salatti[e], D. Brienza[e], R. Piazzolla[e], G. Morgante[f], E. Pace[b], G. Preti[b], G. Micela[g], G. Malaguti[f], A. Caldwell[h], P. Eccleston[h], G. Tinetti[i]
and the
Ariel Mission Consortium (AMC)

[a]INAF/OAA - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italia; [b]Università degli Studi di Firenze - Dip. di Fisica e Astronomia, Via Sansone, 1, 50019 Sesto Fiorentino, Firenze, Italia; [c]AIRBUS Defence and Space, Stevenage, SG1 2AS, UK; [d]INAF/IAPS - Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, 00133 Roma, Italia; [e]ASI - Agenzia Spaziale Italiana, Via del Politecnico, 00133 Roma, Italia; [f]INAF/OAS - Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italia; [g]INAF - Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italia; [h]UK-STFC, RAL Space - Rutherford Appleton Laboratory, OX11 0QX Harwell Oxford, UK; [i]University College of London – Dept. of Physics and Astronomy, Gower Street, London WC1E 6BT, UK

Keywords: Exoplanets, Transit Spectroscopy, Primary and Secondary Eclipses, Atmospheres, Dielectrics Charging, ESD

The Ariel Mission and its orbit

ARIEL (the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey) is the M4 mission of the ESA's Cosmic Vision Program, selected in March 2018 and adopted by the Agency in November 2020 for a launch in 2029, whose aim is to characterize by low-resolution transit spectroscopy and spectrophotometry the atmospheres of over one thousand of warm and hot exoplanets orbiting nearby stars.

The operational orbit of the ARIEL spacecraft (S/C) is baselined as a large amplitude halo orbit around the Sun-Earth system 2nd Lagrangian (L2) point. This virtual point in space is located about 1.5 million km from the Earth in the anti-Sun direction (at 1.01 A.U.), and is confirming the orbit of choice of many current, like JWST, and future (e.g. PLATO) astrophysical missions, because it offers the possibility of long uninterrupted observations in a fairly stable radiative and thermo-mechanical environment.

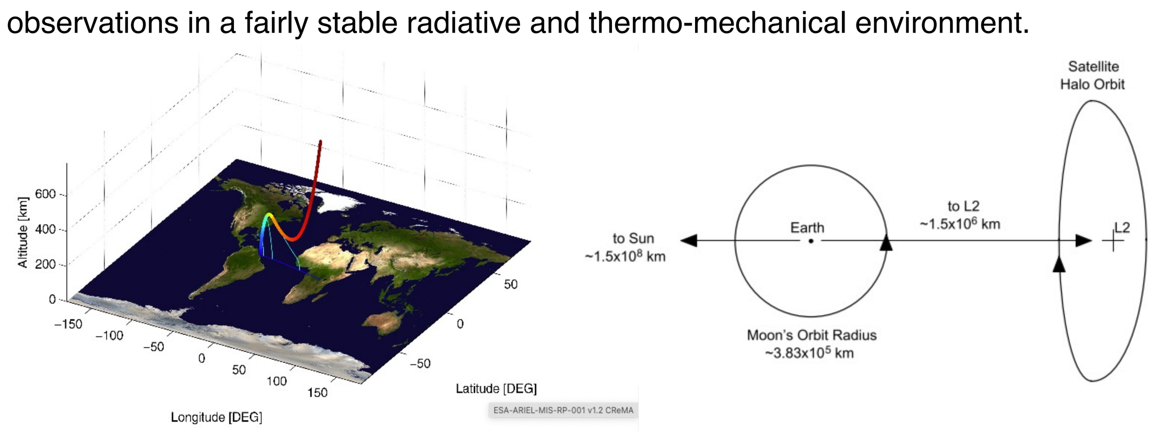

Fig. 1 – Left: An example of an ascent trajectory for a direct L2 transfer injection without intermediate parking orbit. The trajectories of the sub-orbital parts are depicted in cyan. Right: The Ariel halo orbit around L2 with no eclipses allowed during the mission lifetime. Only a short virtual shadow timeframe lasting about 1 hour is expected before the spacecraft release by the Ariane's DLS, once reached an altitude of 10.000 km at least.

The Ariel S/C will be launched, along with the Comet Interceptor Mission, around local noon by an Ariane A6.2 rocket with its Dual Launch Structure (DLS) from Kourou, in the French Guiana. A direct escape orbit injection is planned in the baseline mission profile, being characterized by and involving different plasma environments. This trajectory foresees a single passage through the radiation belts, presently approximated by a somewhat worst case half orbit (10.5 hours) with perigee at 300 km (LEO environment) and apogee at 64000 km (GEO environment). An early quasi-equatorial orbit with an inclination of 0 degrees is assumed as a worst case, after the fairing jettisoning at about 100-150 km of altitude, 4 min following the lift-off. Once released the fairing, the spacecraft will be directly exposed to the Earth's thermosphere and space environment, experiencing plasma regimes from LEO to the direct Solar Wind, once crossed the Earth's radiation belts and the GEO orbits range.

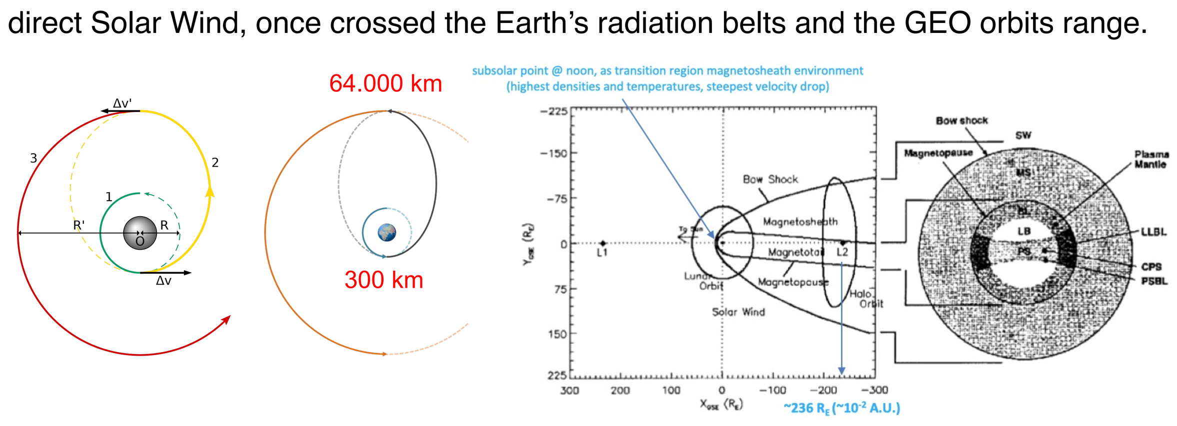

Fig. 2 – Left: Half orbit with perigee in LEO and apogee at GEO. Right: An example of an halo orbit around L2 w.r.t. the dimensions of the Earth magnetotail and magnetosheath indicating the plasma regimes (SW: Solar Wind, MS: MagnetoSheath, BL: Boundary Layer, LB: Lobe, PS: Plasma Sheet, LLBL: Low Latitude Boundary Layer, CPS: Central Plasma Sheet, PSBL: Plasma Sheet Boundary Layer)

The nominal mission duration is 4 years with a minimum extension of an additional 2 years, for a total mission duration of 6 years at least, for which the S/C shall be carefully designed. The space environment presents significant design challenges to all spacecraft, including the effects of interactions with Sun radiation (electron photoemission by impinging EUV light) and charged particles owning to the surrounding plasma environment, potentially leading to dielectrics charging and unwanted ESD (Electro-Static Discharge) phenomena endangering the Payload operations, telecommunications and data integrity.

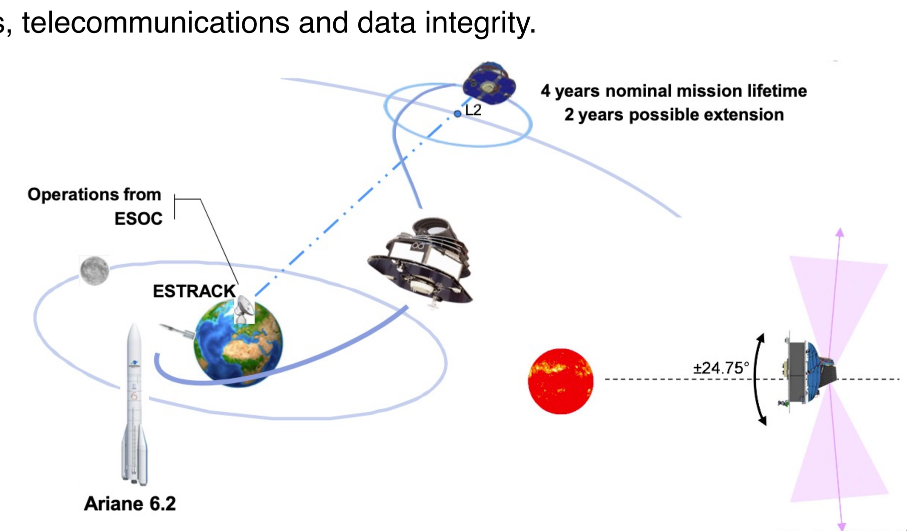

Fig. 3 – The Ariane 6.2 launch vehicle will inject Ariel into a direct transfer towards the libration point L2 of the Sun-Earth system. Launches to L2 will naturally be around noon local time of the perigee, since the apogee is towards the anti-Sun direction.

Here, we present some consolidated analyses and simulations about the ARIEL Spacecraft and Payload dielectrics charging along the transfer orbit, from launch to L2, performed thanks to the use of **SPIS (Spacecraft Plasma Interaction Software)** tool of the **SPINE (Spacecraft Plasma Interaction Network in Europe)** community, a powerful tool to model the 3D spacecraft, the implemented materials, the equivalent SPICE circuit and the space environment along with its charging effects on adopted materials. Similar analyses were already performed during the previous phase by the exploitation of the simpler (and less reliable) **EQUIPOT** tool of the ESA's **SPENVIS (SPace ENVironment Information System)** suite, a w3-based interface to model the space environment and its effects on spacecraft. Similar results were found.

Payload design, environment and materials

The Ariel Payload is conceived modular by design (refer to Fig. 4). The adopted baseline architecture splits the payload into two major sections, the cold payload module (PLM) and the items of the Payload hosted within the spacecraft service module (SVM), i.e. the warm units electronics, along with platform avionic units.

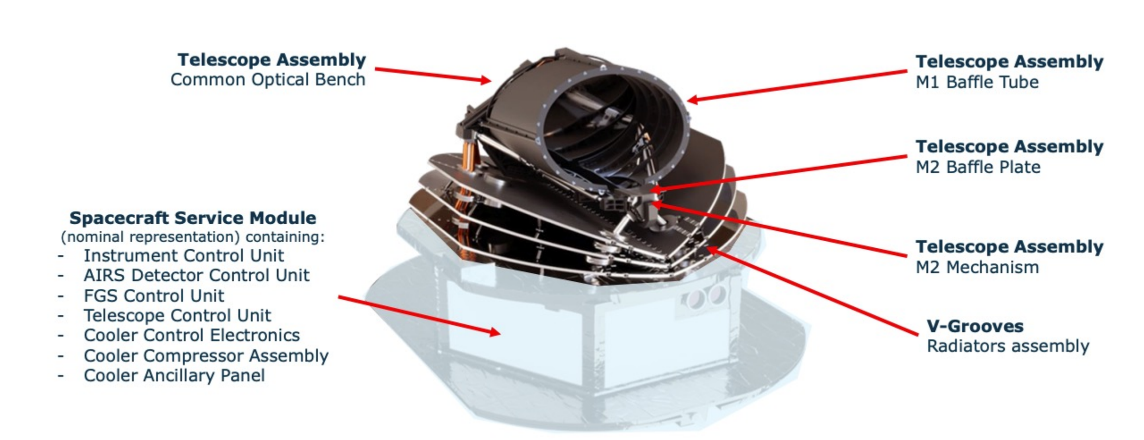

Fig. 4 – Illustration of the Ariel Payload Module (PLM, top) and Service Module (SVM, bottom) composing the whole Spacecraft

The PLM is supported by three bipods mounted onto the Payload Interface Panel (PIP). They are hollow cylinders, made of CFRP filled with low thermally conductive rigid foam. Three V-Grooves (VGs) are adopted as high-efficiency passive radiant coolers, providing the first stage of the PLM cooling system. VGs are made by a simple honeycomb structure of Aluminum alloy, thermally linked to the three bipods (to intercept the conducted parasitic heat leaks through the mounting bipods) and are mechanically supported and thermally decoupled from the PIP by GFRP dielectric struts.

A surface charging analysis, by means of the **SPIS SW suite** has been performed to demonstrate and confirm that, in case of adoption of semi-conductive and dielectrics materials like CFRP and GFRP they don't pose threat to any equipment on the Payload and Spacecraft and the relevant risk associated with electrostatic discharges, due to charge build-up on the material, which may damage nearby equipment, is minimized by means of adopted precautions (e.g. ESD protective coatings on GFRP struts, bonding and grounding). This risk depends on the surface area of the material exposed to space and the unit/equipment configuration w.r.t. the orbit characteristics and Mission phase.

It is worth noting that surface charging phenomena leading to possible harmful ESD are usually of concern at high altitude or polar latitude Earth orbits (auroral zone), especially when the S/C is subjected to eclipses (no electron photoemission balancing the incoming plasma electrons current). The potential (voltage) ranges expected by Ariel are demonstrated not critical and there should not be risk of any powerful ESD, due to the expected voltage differences between the plasma environment, the structure and selected materials. However, the retrieved voltage ranges may raise some concern for specific subsystems sensitive to voltage fluctuations like exposed dielectrics (e.g. exposed connectors hosting pins carrying very sensitive signals).

The main plasma regimes experienced by the ARIEL spacecraft is described and quantified in Table 1. The selected materials along with the Electrical Super Nodes (ESN) definition for the equivalent SPICE circuit are listed in Table 2.

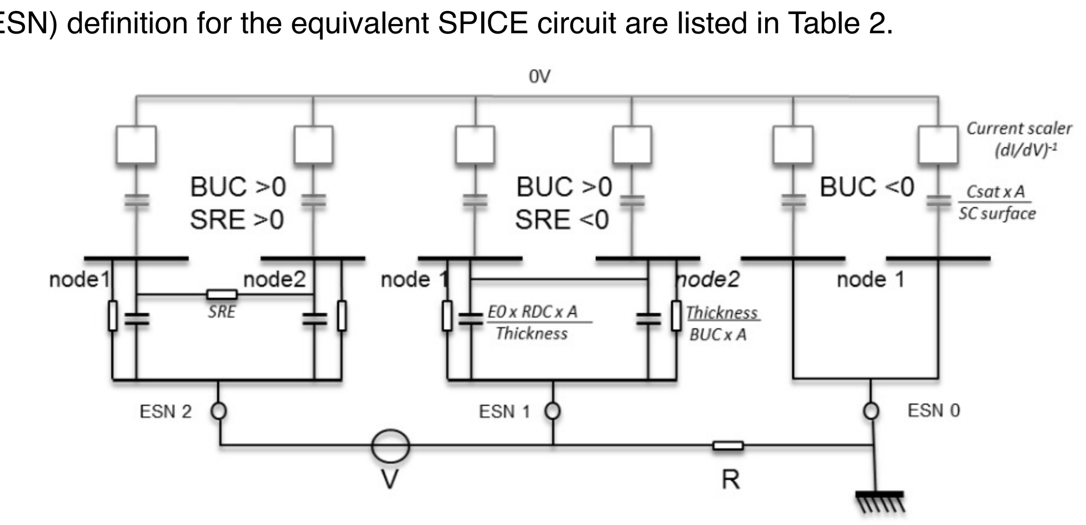

Fig. 5 – SPIS equivalent circuit describing the plasma-S/C interaction by means of materials surface resistivity (SRE) and bulk conductivity (BUC). ESNs define the S/C SPICE circuit.

The spacecraft will spend a little time in LEO, MEO and GEO and significant amount of time when in L2 plasma regimes, but the worst-case high-altitude GEO environment might be of concern, as shown by dedicated simulations.

In addition to the LEO and GEO plasma characterization, the solar wind, the outer magnetosphere plasma environment and relevant effects have to be properly assessed and quantified. These are related to three distinct plasma regimes which can be identified around L2, along the halo orbit. More specifically, the Ariel S/C will spend most of its time in the solar wind and the magnetosheath and a small fraction of the time in the magnetotail. The ratio of time in these environments depends on the selected final orbit. It is worth noting that the boundaries between these regions at L2 show a large variability due to possible variations in the solar wind connected to the solar cycle. The solar wind varies on time scales of tens of minutes to days -short, compared with the orbit of the ARIEL spacecraft around L2- meaning that within a single orbit the spacecraft is likely to encounter several different plasma environments.

In Table 1 are reported the inputs data representing the kinetic energies and temperatures of the involved electrons and ions that have been taken into account to describe the solar wind, the Earth magnetosheath, lobe (magnetotail) and plasma sheet, as defined by the Ariel Environmental Specifications from ESA as well as by the ECSS applicable standards.

Simulations duration is a function of the involved physics and account for the typical plasma densities and frequencies concerning the selected environment.

Input data for surface charging analyses

Orbit/Environment →		LEO (shaded)	GEO (sunlight)	Solar Wind (sunlight)	Magnetosheath (sunlight)	Magnetotail (sunlight)
Parameter	Unit	Averaged value at 1 AU				
Electron Plasma Density	$[cm^{-3}]$	5.31 x 10^3	10	8.7	1.0	0.11
Proton Plasma Density	$[cm^{-3}]$	4.73 x 10^3	10	8.31	0.96	0.11
Helium ion Plasma Density	$[cm^{-3}]$	5.46 x 10^2	N/A	0.39	0.04	N/A
Oxygen ion Plasma Density	$[cm^{-3}]$	3.24 x 10^1	N/A	N/A	N/A	N/A
Electron energy	[K]	1.2 x 10^3	5.8 x 10^6	1.0 x 10^5	3.1 x 10^5	21 x 10^5
	[eV]	0.1	500	8.6	26.7	181
Proton energy	[K]	5.8 x 10^3	5.8 x 10^6	1.2 x 10^5	9.3 x 10^5	63 x 10^5
	[eV]	0.5	500	10.3	80.2	543
Helium ion energy	[K]	5.8 x 10^3	5.8 x 10^6	5.8 x 10^5	9.3 x 10^5	N/A
	[eV]	0.5	500	50	80.2	
Oxygen ion energy	[K]	5.8 x 10^4	N/A	N/A	N/A	N/A
	[eV]	5				
Drift velocity	[km/s]	8	468	468	313	60
Debye length	[m]	0.03	52.6	7.4	38.4	301.5
N_α/N_P	[–]	N/A	N/A	0.047	0.047	N/A

Tab. 1 – Plasma environments

ESN #	Colour		Description	Material	SPIS Adopted Material
0	N/A	N/A	Ground node (virtual node)	N/A	N/A
1		Dark Green	Solar Array Front	Solar Cell	Solar Cell (Cerium doped+MgF2) (125 µm)
2		Liliac	Launcher Adaptation Ring + Main Body + PIP	Carbon Loaded Kapton 160XC (MLI)	Kapton Black (2K) (antistatic polyimide tape)
3		Blue	Solar Array Edges	Exposed Carbon Fibre / Kapton tape edge seal	Epoxy (50 µm) (worst case)
4		Orange	Telescope Baffle	Aluminium	Aluminium (2K)
5		Ivory	Instrument Cavity + TOB	Aluminium (MAP-AQ PUK coating on radiator face)	Aluminium (2K)
6		Cyan	FPE box	Aluminium	Aluminium (2K)
7		Light green	PL Bipods	CFRP	Carbon fibre material properties
8		Pink	V-Grooves	Aluminium	Aluminium (2K)
9		Green	Radiators	White Paint SG121FD	White Paint (PSG121FD 125 µm) (dielectric film)
10		Purple	MGA Antenna	Aluminium	Aluminium (2K)
11		Beige	PL Struts	GFRP	Epoxy material properties
12		Dark Grey	FPE harness connector	Insulator	FPTE/Teflon
13		Pink with red borders	FPE Strut	GFRP	Epoxy material properties
			External boundary		
			Computational volume		

Tab. 2 – ESN and selected materials

For surface charging analyses only charged particles with energies up to 1 MeV have been considered in this study context, as main responsible for surface charging effects. Bulk dielectrics charging, presently not assessed, is normally caused by particles having higher energies (please, refer to ECSS-E-ST-10-04C).

Results, conclusions and future work

The performed analyses and simulations, accounting for the SVM bottom panel hosting the spacecraft solar arrays, always illuminated by the sun light when in L2 (no eclipses allowed), confirm that the expected voltage ranges for the exposed Ariel structure, dielectrics (e.g. GFRP) and semiconductors-like materials (in terms of surface resistivity value, e.g. CFRP) are not critical (all values below 100 V, as differential voltage w.r.t. the plasma reference potential) and there is no considerable risk of dangerous electrostatic discharges. However, the found ranges, especially the GEO ones, may still raise some concern for specific subsystems sensitive to voltage fluctuations, that shall be further assessed at system level accounting for the different charging times needed for reaching a plateau (equilibrium voltage) and the possible implementation of specific precautions (e.g. ESD coatings and metallic protective caps for the exposed connectors).

Additional effects due to deep dielectrics charging caused by energetic particles should be assessed in the future by AMC in collaboration with the S/C provider (Airbus DS), as not covered by the present Payload surface charging analyses. Longer simulations are also needed in order to clearly show, by the plotted curves, the achievement of steady state regimes, as defined by the 2nd Kirchhoff law.

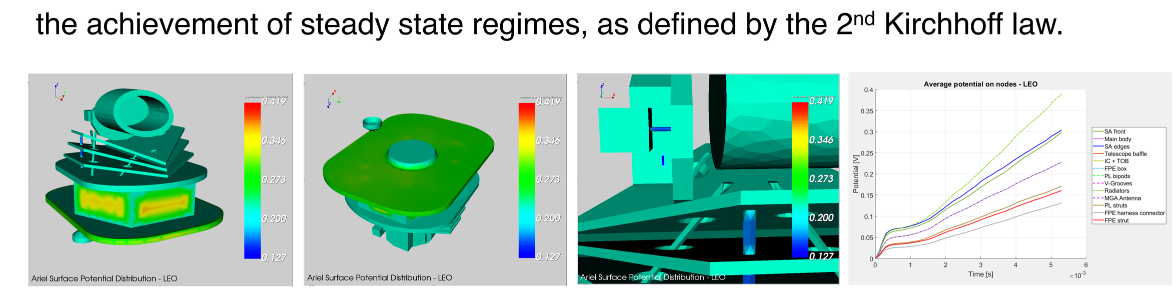

Fig. 7 – LEO (virtual shadow)

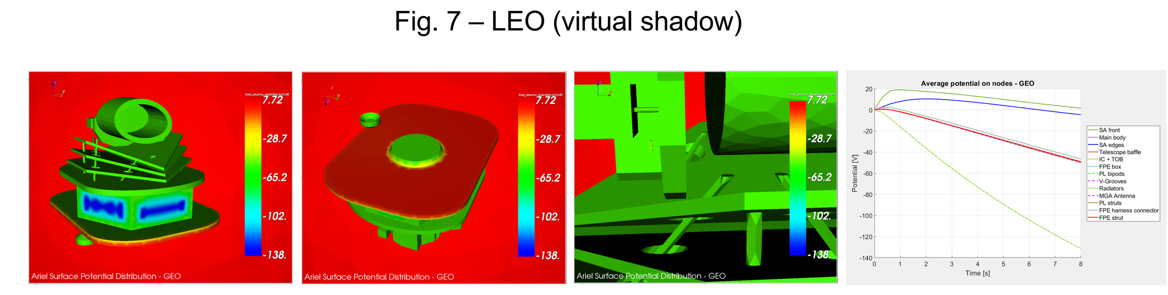

Fig. 8 – GEO (sunlit)

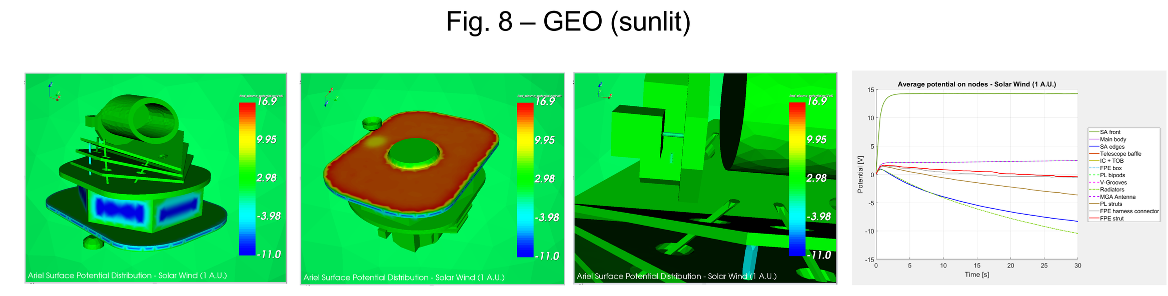

Fig. 9 – Solar Wind (sunlit)

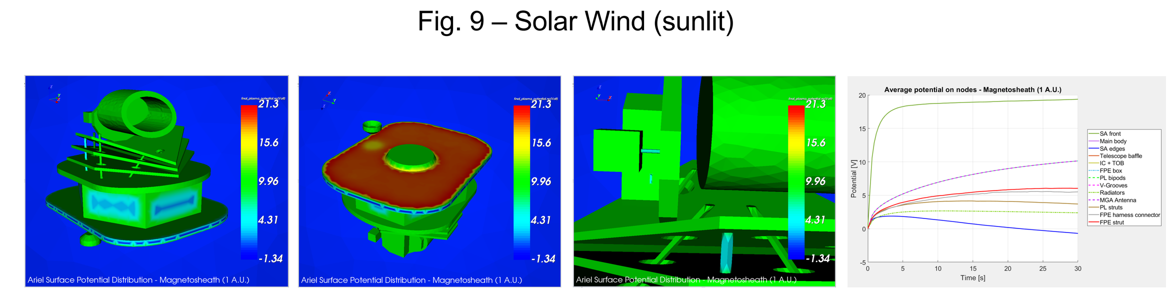

Fig. 10 – Magnetosheath (sunlit)

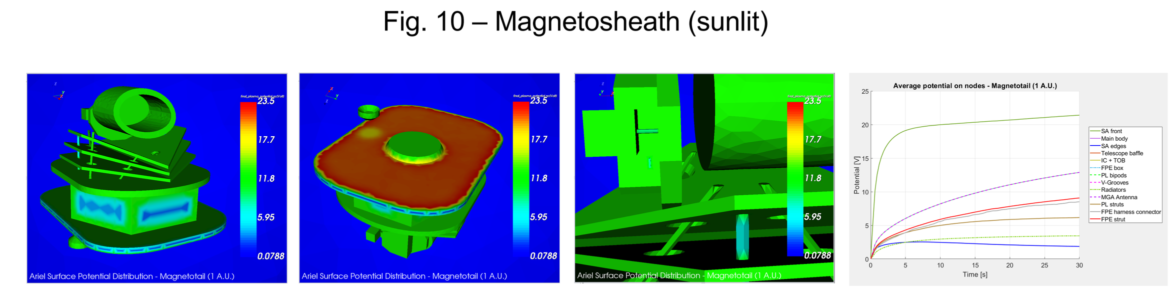

Fig. 11 – Magnetotail (sunlit)

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Mauro Focardi (Corresponding Author), e-mail: mauro.focardi@inaf.it and *Pierpaolo Merola (Presenter), e-mail: pierpaolo.merola@inaf.it
INAF/OAA - Arcetri Astrophysical Observatory, Largo E. Fermi 5 - 50125 Firenze, Italy

Acknowledgement: this study has been supported by the *Italian Space Agency (ASI)* thanks to the ASI-INAF agreement n. 2021-5-HH.2-2024 *"Scientific activity for the ARIEL Mission – B2/C/D1 Phases"*