LUNAR GRAVITY EXPLOITATION TO ENHANCE X-RAY TELESCOPE OPERATIONAL FLEXIBILITY THROUGH FRACTIONATED ARCHITECTURE. S.Di Marco[1], M.M.Civitani[2], A.Frigeri[3] and M.Lavagna[1], [1]Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy - stefano2.dimarco@mail.polimi.it, michelle.lavagna@polimi.it, [2]INAF-OAB, Via E. Bianchi 46, 23807 Merate (LC), Italy - marta.civitani@inaf.it, [3]INAF-IAPS, via Fosso del Cavaliere 100, 00133 Roma, Italy - alessandro.frigeri@inaf.it

Introduction: The Moon has gained renewed interest in the last decade for scientific investigation, technology testing and industrial exploitation, thanks to its vicinity and such a different environment from Earth. The Moon, even if just three days away from Earth, is a perfect Deep Space training ground which motivates to be the first next step in worldwide space exploration roadmaps. A relevant example in this framework is the NASA's Artemis program and its Lunar Orbital Platform – Gateway to be launched in 2024 to serve as multi-purpose Deep Space infrastructure, to extend the human presence to the cis-lunar environment and support lunar surface and interplanetary activities.

Among the latter, deep space observations performed from a lunar outpost are privileged, thanks to the clean and quiet field of view, coupled with the Earth vicinity for servicing. Therefore, the paper proposes to exploit the unique lunar dynamics environment to enhance X-ray telescopes state of the art performance, already gained with predecessors like NASA's NuSTAR. In particular, the multi-gravitational environment offered by the Earth-Moon system and the lunar tidal locking are here exploited to settle a fractionated architecture for the instrument with its detector located on the lunar surface and the mirror in space, orbiting the Moon. Such architecture is crucial for the telescope scientific operability enhancement, as briefly discussed in the followings.

Scientific rationale: Imaging astronomical sources with extremely high angular resolution could enable significant advances in our understanding of the universe. As an example, the event horizon shadow of the supermassive black hole in the active galaxy M87 has been imaged at the wavelength of λ=1.3 mm with angular resolution around 25 μas by an Earth-sized interferometer [1]. Comparable angular resolution has not been reached in other bands. The Chandra and the NuSTAR telescopes achieved so far, the best results in the X-ray band. Nevertheless, their angular resolutions are orders of magnitude higher, respectively 0.5 arcseconds and 60 arcseconds, in the low and in the hard X-ray energy band [2,3]. X-ray imager designs with μas angular resolution have been proposed [4,5,6] but the grazing reflection concept limits effective collecting area. A complete change of approach, based on light refraction, could offer new possibilities. As far as hard X-rays are concerned, the first refractive lens was introduced very recently, in 1996 [8]. Such a lens is governed by geometric standard optics equations. The focal length of a symmetric double convex lens with identical radii of curvature R of both surfaces is given by $f = -R/(2\delta)$. In the X-ray bandwidth, the difference of the refraction index between vacuum and light materials is very tiny (around 10^-6), which imply very long focal length. Nevertheless, a simple concept with a single refractive lens could guarantee an unprecedented collecting area if its thickness is limited in order to prevent photon absorption. With the right choice of materials and sizing, radiuses of curvature of the order of 10 - 40 m are possible. Taking into account a minimum thickness of 1mm and a focal length around 70'000 km, a lens of Beryllium with a radius of curvature of 31 meters could guarantee an effective area of around 1900 cm^2 @ 40 keV. This is almost 10 times NuSTAR collecting area at the same energy and could be achieved with a single lens. Taking into account the negligible weight (few kg) and exceptional optical performances this would enable significant advances in X-ray astronomy.

Concept: Hence, a key requirement to X-ray telescopes performance enhancement stays in increasing their focal length to tens of thousands of km, which clearly drives to decouple the optics from the detector unit. By leveraging the Earth-Moon gravity system and its tidal locking, the paper discusses the scientific and technological viability of setting the detector on the Moon surface while letting the optics orbiting on a non-keplerian trajectory around the EM-L2, designed according to the focal length and strict pointing requirements. The selection of the site for the deployment of the sensors requires a multi-scale knowledge of the morphology and the nature of the different terrains of the Moon's surface. At

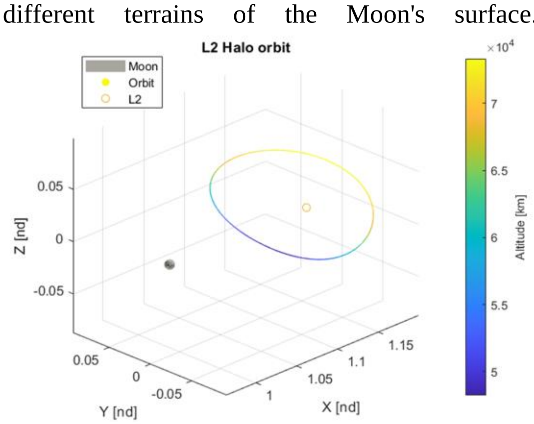

Figure 1. EM-L2 Halo orbit in the rotating non-dimensional reference frame centred in the Earth-Moon barycentre.

the deployment scale, we must consider the physical properties of the lunar soil, the regolith [8].

Both the Earth-Moon system gravity field and the Moon irregular mass distribution effects are included in the dynamical model, even if the Moon surface vicinity is quite contained (mean Moon distance ~ 72’000 km) since the selected trajectory oscillates about the EM-L2 point. The inclusion of these phenomena allows quite faithfully representing the natural dynamics, fundamental to assess the motion stability of the mirror satellite with respect to the detector located on the lunar surface. Moreover, external disturbances are considered too, which are the Sun's gravity attraction and the Solar Radiation Pressure, and the real dynamics, associated with the Moon’s ephemeris position around the Earth [9,10]. These are quantified by the pointing stability, defined by the relative position between the orbiting mirror and the sensor on the surface and by the satellite attitude during its motion, which define the ranges in which the image can be reconstructed. A refractive lens can be inserted into the system without alteration of the beam direction and relevant focal spot aberration. Negligible effects are expected from the orientation of the detector with respect to the Line of Sight (LoS) of the system. As a consequence, the alignment of the optics with respect to the pointing direction, and of the detector module with respect to the LoS can be relaxed up to a one-degree level. On the contrary, the accuracy in the knowledge of the pointing direction will contribute directly to the final reconstructed image and should be of the order of a few μas. Next, the long focal length of the lens minimizes the chromatic aberration. Simulations show that it can be optimized according to the orbit for a certain energy range, so that variations in the relative distance up to ±1000 km are acceptable.

Dynamics: The trajectory chosen to fulfil the scientific instrument characteristics presented above belongs to the Halo family bound to the EM-L2 Lagrangian point [11], with a 14.78 days orbital period and Ax = 24’785 km, Ay = 71’425 km and Az = 24’690 km amplitudes. Figure 1 depicts the selected orbit and its distance from the detector on the Moon's surface. For this first iteration, the detector is placed at latitude 0° and longitude 180°, i.e. centred in the far side of the Moon to minimize the Earth noise and retain a free celestial sphere visibility all over the mission long lifetime (i.e. years). The EM-L2 Halo family is selected to retain the trajectory over the far side low latitude band of the Moon, where the amplitude Az allows to guarantee the LoS with the detector and to retain the ground track on the Moon's surface to low latitudes. That choice also ensures low station keeping coupled with deep space observation windows maximisation. Figure 2 shows the ground track for two orbital periods, for which the trajectory is periodic accounting also for the inclination of the Moon's spin axis over its orbit around the Earth. In addition, the Ax amplitudeis centred on the nominal value of the telescope focal length of 72’000 km and it offers a wide observation window, of approximately 103.5 hours per orbit period, that turns into 2570.2 hours per year. These properties translate in the maximisation of the observation events associated with the X-ray sources, remarked as of interest by the scientists and reported in Figure 2.

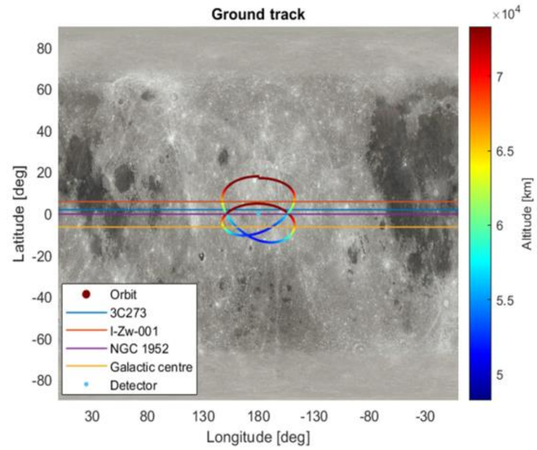

Figure 2. Ground track on the lunar surface of the L2 Halo orbit, some of the x-ray sources considered and the position of the detector.

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