SOLAR SYSTEM OBSERVATIONS WITH THE ESO EXTREMELY LARGE TELESCOPE

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Abstract. By 2028, the first ever 39m-telescope will have its first light at the ESO Cerro Armazones site (Chile). The first generation instruments of the Extremely Large Telescope (ELT) will enable observations in imaging and spectroscopy that combines great sensitivity with an exquisite spatial resolution. We present several science cases for the ELT from the Solar System, involving comets, Main Belt Asteroids, Trans-Neptunian Objects (TNOs), and the giant planets (atmospheres and satellites).

Keywords: ESO ELT, Solar System, Observations, Inaging, Spectroscopy, Adaptive optics

1 Introduction

Today's major challenges in planetary science can be summarized in three points, as described in the NASA Planetary Science and Astrobiology Decadal Review 2023-2032 (`https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032`): 1) Origins: evolution of the protoplanetary disk, accretion in the Outer Solar System (how and when did the dwarf planets and cometary bodies form beyond the giant planets? etc.), origin of Earth and inner Solar System bodies, 2) Worlds and Processes: impacts and dynamics, solid body interiors and surfaces, atmospheres, exospheres and climate evolution, giant planets structure and evolution, etc. and 3) Life and habitability: exoplanets, searching for life elsewhere, etc. These questions can be tackled with the new ESO/ELT, thanks to the combination of the superb sensitivity of its instruments and the exquisite spatial resolution. Figure 1 displays the spatial sampling as a function of the distance from the Sun, as well as the apparent diameter in pixels with MICADO (Multi-AO Imaging Camera for Deep Observations) for some prominent objects. For instance, Jupiter's largest satellite Ganymede can be sampled over 1000 pixels, which gives us access to its fine geological structures at the surface (about 30km resolution, from a ~10 mas spatial resolution) and enables long-term monitoring of the geological activity.

2 Comets and Main Belt Asteroids

The minor bodies of the Solar System (comets, main belt asteroids, interstellar objects, trans-Neptunian objects, Centaurs, satellites) are the residuals of planetary formation and hold clues on how and when the planets formed. Observations in imaging and spectroscopy in the visible and infrared domains lead to constraints on surface composition, shape models (and density determination), geological and composition heterogeneities (when the spatial resolution is satisfactory). For comets, the chemical composition of the coma can be unveiled.

The surface composition of the Main Belt Asteroids (mainly located between Mars and Jupiter) is already well constrained from extensive spectroscopic studies with 3m+ class telescopes since the '50s. The new contribution

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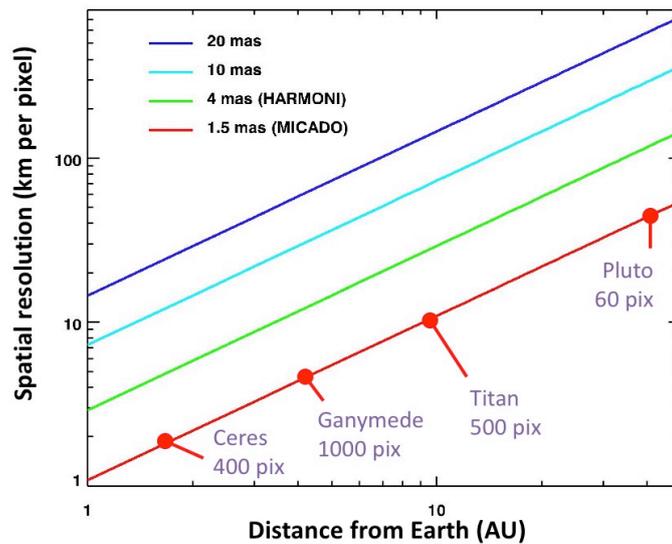[6] University of Oxford, Keble Road, OX1 3RH, Oxford, UK

Fig. 1. Spatial sampling (km per pixel) as a function of distance from Earth (AU). The apparent diameter in pixels is given for some prominent objects using the MICADO imager 1.5 mas pixel scale. The final expected resolution (after deconvolution) should be about 10 mas.

of ELT to this domain would be to study the spectral properties of binary asteroids (more than 100 candidates) to constraint their formation mechanism. Also, the study of the shape and density of the asteroids in the 30-100km range in diameter would complete the existing dataset of objects larger than 100km (VLT+SPHERE/ZIMPOL, see Vernazza et al. 2021) and those <30km that were visited by various Space Missions. Figure 2 shows the largest asteroid Ceres, as seen by the NASA/Dawn mission (*in situ*) compared to a SIMCADO simulation of a MICADO image in the H band. The main geological structures can be easily identified.

Comets can be studied by different instruments. METIS (Mid Infrared ELT Imager and Spectrograph) will enable spectroscopic observations in the 3-13 μm range of the dust in the coma. Such observations are important for measuring the fraction of crystalline relative to amorphous silicates (indicative of the comet forming region) and can also be used to search for the presence of aliphatic and aromatic components in the dust (see e.g. Ootsubo et al. 2020, Icarus 338, 113450). ANDES (ArmazoNes high Dispersion Echelle Spectrograph) aiming at the 0.4-2.40 μm range will be a key tool for measuring isotopic ratios for different species in the coma (e.g. $^{14}N/^{15}N$ in N_2^+ or NH_2 , $^{12}C/^{13}C$ in CO^+, C_2 or CN). Such isotopic ratios are important tracers for the origin of comets.

3   Trans-Neptunian Objects (TNOs)

More than 3,500 objects have been discovered since the '90s (over $\sim$70,000 predicted) in the region beyond Neptune (also called the Kuiper Belt), the most famous of them being former planet Pluto. Typical apparent magnitudes peak over 20-22 in the visible and over 18-20 in the NIR: these objects are therefore extremely challenging to observe, even with 8-10-m class facilities. Despite an extensive observational effort from the community over 25 years, spectra are available in the vis-NIR for less than 100 objects and size and albedos for $\sim$150 objects (mainly using ESA/Herschel measurements with the radiometric method). From these early studies, three types of surfaces emerged: the methane/nitrogen dominated objects (mainly the largest bodies as Pluto, Eris and Makemake), the water ice dominated surfaces (such as Haumea, Orcus or Quaoar), and the "red matter" dominated surfaces, with a steep continuum in the visible and no ice absorption features in the NIR (although this "red matter" has not been fully identified so far). The latter class is populated with a significant fraction of objects with very low signal-to-noise ratio (SNR) spectra (in the J>19 range), blurring the surface composition interpretation, given the (apparent) lack of absorption features.

Although JWST will cast some light on the primitive ice content of a large number of TNOs, the ELT will provide the first spatially resolved data for the Kuiper Belt (besides Pluto and Arrokoth, targets from the NASA/New Horizons mission). HARMONI (High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph) will enable the first surface composition contrast mapping of the largest dwarf
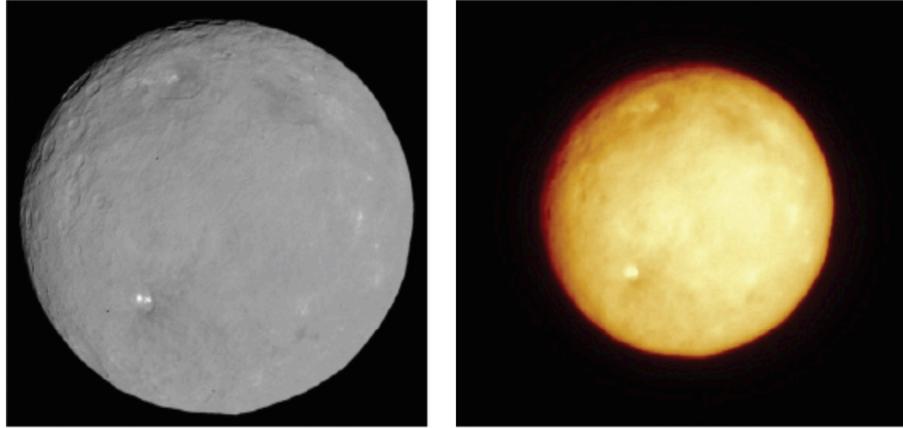
Fig. 2. The largest Main Belt Asteroid Ceres as seen *in situ* from NASA/Dawn mission (left) and simulated from SIMCADO for the ELT/MICADO 1.5 mas pixel scale mode in H band, from an apparent diameter of ∼600 mas (right). The simulated image was not deconvolved. The best spatial resolution that could be achieved after deconvolution should be around 10 mas.

planets in the 0.4-2.4 μm range at R∼3000, but will also allow us to reach any TNO in the J=18-22 magnitude range (above 1000 objects) with a 10-100 SNR NIR spectrum. Additional thermophysical information can be provided by both MICADO in its high resolution spectroscopy mode (up to R∼20,000) and HARMONI (up to R=17000 in the J, H and K bands). Figure 3 shows a HARMONI HSIM simulation of a ∼1300km TNO covered with various amounts of crystalline water ice.

The main breakthrough about TNOs will undoubtedly come from the study of binary (or multiple) systems by the combination of spatially resolved IFU NIR spectroscopy from HARMONI, with fine orbit determination in the astrometric mode of MICADO. The surface composition of both components will constrain the formation scenarios while the determination of the orbit parameters of the system will gives us access to the mass and density. While numerous known candidates can be targeted with ELT, the Vera-C.-Rubin Observatory will provide us with about 30,000 new TNOs in the next decade, offering new exciting science case opportunities for the ELT.

4 Satellites and atmospheres of the Giant Planets

The origin of the giant planets' satellites is still debated: were they formed *in situ* or captured? The known spatially resolved images show various stages of geological resurfacing (craters, cracks, etc.), and activity (plumes, volcanoes, etc.), while spectra can highlight the contrasts in surface composition (see for instance the VLT/SPHERE observations of Ganymede by King & Fletcher 2022 and references therein). All these features are tracers of their origin and further evolution. As illustrated in Fig. 4 for the Galilean satellites Io, Europa, Ganymede and Callisto, with an 8m imaging facility we have access only to partial information such as large physiographic provinces and contrasts (polar caps, bright/dark areas) and the very largest impact craters or volcanoes. With the ELT 12 mas typical spatial resolution (Fig. 4, second row) we can document the local terrain structure, small impact craters and rays from large craters, linae on Europa and small volcanoes on Io, while getting also the local spectral information when using HARMONI Integral Field spectroscopy. For Ganymede observations, a goal of 10 mas final spatial resolution (on deconvolved images) would give us a 30km scale on its surface, to be compared to the ∼20km achieved by NASA/Juno. We can therefore envision a high quality long term monitoring of the geological activity and features of Ganymede and the other satellites with the ELT instruments.
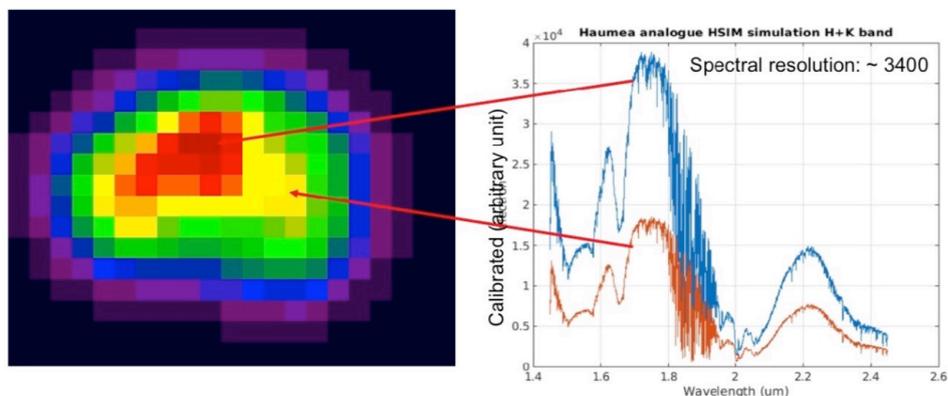
Fig. 3. HARMONI HSIM simulation of a ∼1300km body in the Kuiper Belt (left) covered with various amounts of crystalline water ice. The colors (from purple to red) show increasing signal intensity in instrument units. Such an object is not spatially resolved with existing facilities: the first contrast maps will be obtained with the ELT. The right panel shows the spectral extraction in the H+K band for 2 different pixels at R=3400.
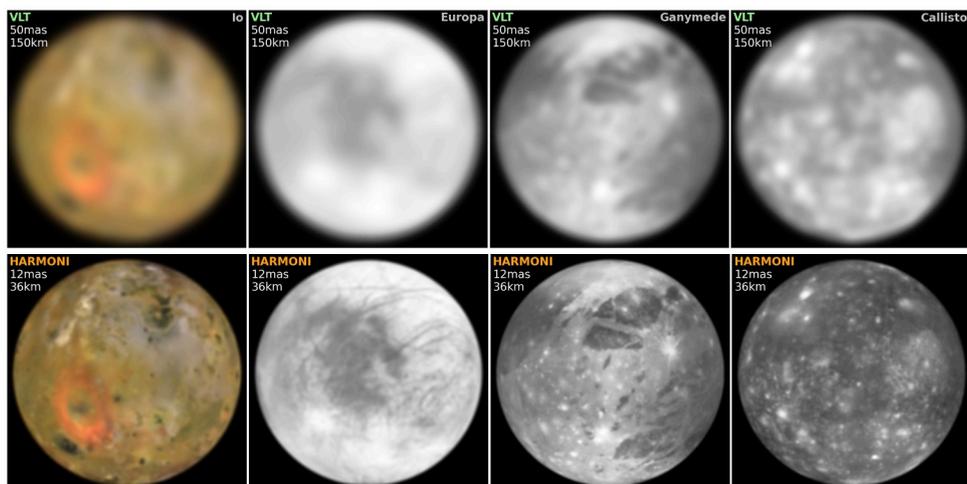

Fig. 4. The Galilean satellites Io, Europa, Ganymede, Callisto (from left to right) as seen from (top to bottom) VLT (50 mas spatial resolution) and ELT (12 mas spatial resolution). With the ELT/HARMONI instrument, each pixel will also contain the spectral information. The original U.S. Geological Survey (https://www.usgs.gov/) global mosaics of the moons, which are a combination of NASA/Galileo and Voyager images, were simply scaled in pixel size to the typical spatial resolution of each facility to visually illustrate the gain in resolution.

The atmospheres of giant planets provide a living laboratory to investigate large-scale fluid dynamics and physico-chemical phenomena. High resolution imaging will provide unprecedented clues to the atmospheric dynamics and global circulation, revealing detailed views of clouds, storms, vortices, and auroras and how these features move and change with time (thanks to long term monitoring with the same instruments). From spectroscopy, for instance, the finest spatial scales of tropospheric CH_4/H_2/aerosol distributions can become accessible for Neptune with HARMONI (and may be Uranus) taking advantage of the 825nm hydrogen collision induced absorption band. HARMONI Single Conjugate AO system is currently aimed at observing objects up to 2.5" in diameter, but in practice it might be able to deal also with larger diameter AO reference objects such as Uranus. Ice giants' observations will require mosaicing techniques to cover the explored regions.

5   Conclusions

The ELT will provide an exquisite set of instruments for observations with both a superb sensitivity and a fine spatial resolution to tackle the most exciting pending questions about the Solar System. We have to keep in mind that the ELT complexity will be substantially higher than for existing facilities, as regards operations (pointing, mirror stabilization, Adaptive Optics operations from both the telescope and the instruments, etc.), observations (hardware constraints, actual atmospheric conditions to be translated into observation performances, scheduling, etc), data volume management and analysis. The main challenge for us is to be prepared for: 1) refining AO capabilities for non-sidereal moving and extended targets of the Solar System, 3) image and spectral cubes analysis and deconvolution in particular in the framework of the ANR APPLY project by Neichel et al. on Point Spread Function (PSF) estimation for AO observations, 3) carefully defining phase 1 and 2 observations constraints for ESO for our Solar System targets. In this framework, the ELT Solar System Working Group aims at proposing relevant science cases for the various ELT instruments to be scientifically and technically prepared for the first light.

References

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