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ORIGINAL ARTICLE

UV exploration of the solar system

Jean-Yves Chaufray[1] · **Laurent Lamy**[2] · **Philippe Rousselot**[3] · **Mathieu Barthelemy**[4]

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Abstract

The study of the Solar System is fundamental to answer key questions from space agencies, as outlined in their strategic plans, about the content, origin, and evolution of the Solar System and the potential for life elsewhere. The UV spectral range is a crucial window to investigate a large area of phenomena associated with this objective, ranging from the surfaces to the atmospheres and magnetospheres of the Solar System bodies. In this White Paper, submitted to ESA in response to the Voyage 2050 call, we present a few examples of science issues that could be addressed about surfaces, atmospheres, and magnetospheres for different objects in the Solar System using UV observations. After the planned termination of the highly successful Hubble Space Telescope (HST), a new multi-objects UV observatory with UV spectro-imager to map the surfaces, atmospheres, and auroral regions of the different objects of the Solar System, and spectropolarimeter to provide measurements on the surface texture, atmospheric aerosols, surface pressure for KBOs, and magnetic field measurements, would be needed to answer the major questions presented in this paper and to open new possibilities of exploration in the Solar System and beyond.

Keywords Solar system · UV spectroscopy · UV polarization

✉ Jean-Yves Chaufray
chaufray@latmos.ipsl.fr

[1] LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt 78280, France

[2] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, Meudon 92195, France

[3] Institut UTINAM UMR 6213 / CNRS, Univ. Bourgogne Franche-Comté, OSU THETA, BP1615, Besançon 25010, France

[4] Univ. Grenoble Alpes, CNRS, IPAG, Grenoble 38000, France

1 Introduction

The study of the Solar System is fundamental to answer key questions from space agencies, as outlined in their strategic plans, about the content, origin, and evolution of the Solar System and the potential for life elsewhere. The UV spectral range is a crucial window to investigate many phenomena associated with this objective, ranging from the surfaces to the atmospheres and magnetospheres of Solar System bodies. UV measurements of the surface albedo and polarisation can provide information on the surface activity (volcanism, plumes), its composition in water ices / organic matter, and its texture (particle size, roughness, porosity). Remote UV measurements are also a very useful tool to investigate the composition of the planetary atmospheres and aerosols' content, especially for objects far from the Sun, where in-situ missions will not be sent in the near future. Finally, UV studies (for example, from the Hubble Space Telescope (HST) or Hisaki) have provided a large amount of information on the planetary magnetospheres of the giant gas planets Jupiter and Saturn and their electromagnetic interaction with their satellites that can be extended to the icy giant planets (Uranus and Neptune) and used to interpret the possible weak detection ofauroral emissions from exoplanets. The planned termination of HST will prevent scientific UV observations of the Solar System at large aperture with high spectral resolution in the future. In this White Paper, submitted to ESA in response to the Voyage 2050 call, we will summarize the major science issues that could be addressed about surfaces, atmospheres, and magnetospheres for different objects in the Solar System using UV observations. We will then give a description of the observations required to answer these questions and a possible mission that could be designed to perform these observations.

2 Scientific questions

UV observations uniquely probe the surface of telluric bodies of the Solar System. They diagnose their volcanic and plume activity, their interaction with the solar wind and their composition in the frame of space weather and exobiology/habitability fields [1]. In this section, we will not present an exhaustive list of all research areas but only focus on a few examples of current active research.

2.1 Planetary surfaces

2.1.1 Surface activity in the solar system

Plumes of water ice particles and water vapor with salts and organic material, possibly formed by hydrothermal activity, have been observed at the surface of Enceladus, from fissures across its south polar region ("tiger stripes"), by several measurements (e.g. [2]). The tidal deformation of Enceladus is a source of heat and stress driving its geological activity, opening cracks at apoapse of Enceladus and closing cracks at periapse. Its surface near the south pole could have been resurfaced in the recent past [3]. The plumes could come from a global liquid water ocean present below its surface as suggested by magnetic and gravity measurements, surface morphology, and physical libration [4] rather than sublimation at the surface. The water vapor ejected by the plumes from Enceladus is the main source of oxygen in the plasma of the Saturnian magnetosphere and also the source of the extended E ring of Saturn [5]. Part of the E ring materials bombard the surface of the leading hemisphere of Tethys and Dione and the trailing hemisphere of Mimas producing a brighter surface in UV than the opposite hemisphere [6–8]. The UVIS instrument has estimated the average amount of water released from geysers from stellar occultation [2].

UV emissions (HI 121.6 nm and OI 130.4 nm) associated to a plume activity have also been observed by the Hubble Space Telescope (HST) at the surface of Europa [9]. During transits of Europa across the disc of Jupiter, absorption features were observed from HST/STIS images [10].

As for Enceladus, the plumes activity on Europa could be due to tidal stress opening and closing fractures at the surface, but the frequency of this activity on Europa is still unknown due to the limited set of observations. New observations are then required to confirm this scenario. This tidal dissipation provides constraints on the interior and the liquid water layer [3]. The comparison between Saturn disc occultation by Enceladus and Jovian disc occultation by Europa shows diffences between the plumes on Enceladus and Europa, with more massive but more sporadic jets on Europa than Enceladus [11].

Io's surface is known to be very active with an important volcanic activity also triggered by the large tidal stress of its surface. This volcanic activity is the main source of a small atmosphere at Io. It is also the main source of sulfur and oxygen ions of the Jovian magnetospheric plasma. These energetic ions can bombard the surfaces of other Jovian satellites like Europa or Ganymede leading to radiolytic decomposition of their icy surfaces and contributing to the formation of their exospheres. UV emissions from the Io plasma torus, produced from Io's volcanoes can be used to study the effect of the volcanic activity at the Io surface on the Jovian magnetosphere [12–15]).

The surface of Pluto has been observed for the first time by the New Horizons flyby on July 152,015. These observations revealed an unexpected wide diversity of geological structures, mainly formed of N_2 icy plains. Recent geological activities could have been or still be present on Pluto, such as cryovolcanism in the Virgil Fossae region [16].

Questions still open that future missions should focus on are What is the source of the plume activity of Enceladus and Europa? What is the amount of gas/ices/organics in the plumes and their composition? What is their potential for habitability? Can these plumes modify their tenuous atmospheres? Is there any direct relations between the volcanic activity of Io and Jovian aurorae? Are Pluto and other Kuiper Belt objects (KBOs) still geologically active?

2.1.2 Surface texture and composition

The texture and composition of numerous objects in the Solar System remains poorly known, while it is fundamental to know it to understand the origin of the different objects in the Solar System, the processes of their formation.

Space weathering of surfaces (the impact of solar wind particles and micrometeoroids with a surface) can alter the optical properties of the surface at different wavelengths. The formation of submicroscopic iron (SMFe) by impact of micrometeoroids or sputtering by solar wind ions can explain the variations of the optical properties observed at the surface on the Moon [17]. The Moon is the best object in the Solar System to study the effects of space weathering on the surfaces and their consequences on their optical properties at different wavelengths. Some regions of the Moon, called “swirls”, don’t show the same optical properties as the surrounding regions associated with space weathering. These regions are associated to magnetic crust that could protect the surface from solar wind creating a local mini-magnetosphere. In that case, only micrometeoroids can alter the surface properties. The UV observations by the Lunar Reconnaissance Orbiter showed these regions are “less blue” in FUV (160 nm – 200 nm) than the surrounding regions which is consistent with less weathering. In a space weathered region, the formation of SMFe masks the absorption by silicates making the region “less blue” [18]. A systematic study of these effects could lead to deriving a method to date the exposure time of a surface to incident plasma and in the future could be used to interpret observations of exoplanet surfaces. The permanently shaded regions (PSRs) are regions that are never illuminated and where water ices can be stable. The lunar PSRs have been found to be highly porous compared to the average lunar regolith from UV reflectance [19]. The origin of the high porosity is not known but could result from a low thermal cycling or to charge effect inside the PSRs [20]. PSRs exist on every object with craters near its polar axis and a systematic survey of their texture and amount of water ices would be useful for a possible future exploitation.

The surfaces of the satellites of Jupiter and Saturn are permanently bombarded by the energetic particles of the Jovian magnetosphere. The effects of this irradiation on the composition and texture is not well known and is difficult to reproduce in the laboratory with similar conditions [21]. The irradiation of an icy surface damages the grains, depending on the incident energy and the local properties of the ice. It could possibly affect the amount of amorphous and crystalline ices in the near surface (< 1 mm). The amount of surficial amorphous ice is larger at Europa (the most irradiated Jovian satellite) than Ganymede while only crystalline ices have been detected on Callisto, (the least irradiated Jovian satellite) [22]. The surface ices of the inner satellite of Saturn are mostly in crystalline state that could be due to a lower plasma flux in the magnetosphere of Saturn compared to the Jovian magnetosphere [22].

The detection of a large quantity of trapped gas (“micro-atmospheres”) composed of O_2 and O_3 within the surface ices resulting from this irradiation [23, 24] was not expected and could be a widespread process of ozone formation in the Solar System and outside.

Knowing the composition of the surface ices and trapped gas is important to better understand the chemistry induced by surface sputtering [25].

The determination of the composition (organic and ices, dusts) of the crust of comets, asteroids, Kuiper Belt objects (KBOs), and other primitive bodies in the Solar System is fundamental to understanding the origins and formation of the planets. For example, the recent unexpected detection by Rosetta of large amounts of O_2 in the coma of comet 67P/Churyumov Gerasimenko [26] compared to the low O_2 abundances in the Universe has led to the suggestion of several new processes to explain it. However, the current set of observations is not sufficient to determine if the formation of substantial amounts of O_2 is due to in-situ production after or before its formation.

UV spectral reflectance of a few KBOs (Makemake, Haumea, Hi’iaka, Namaka, Pluto, Charon) and the Centaur Chiron were performed by HST/COS between ~260–320 nm. These observations indicate an heterogeneity in the UV albedos of KBOs. The albedo of Makemake was rather flat (~ 0.5) without detected absorption structure. Haumea and its two satellites (Hi’iaka and Namaka) are very bright in UV, indicating icy surfaces. An absorption feature near 305 nm was observed for Haumea possibly due to OH resulting from the radiolysis of surface dominating H_2O-ice constituent or SO_2 frost. The size of the two satellites of Haumea was partly constrained by these observations [27].

Recent observations by New Horizons of several KBOs (Pluto, Charon, Arrokoth) have confirmed the presence of large amounts of ices with organics at their surfacess. On Pluto, a large diversity of geological structures with bright and dark regions composed of ices (N_2, CO, CH_4), organics tholins and rocks have been observed. The surfaces of Charon, Nix, and Hydra are dominated by water ices, with a dark region on Charon (Mordor Macula), that could be due to the presence of a hydrocarbon layer formed from methane escaping Pluto and captured in the cold regions of Charon [28].

A systematic study of the surfaces of a large number of KBOs is needed to understand if Pluto and its satellites are representative of the KBOs or not. Such a survey is only feasible from ground-based facilities composed of different telescopes observing at different wavelength ranges. The recent detection of interstellar objects (like 'Oumuamua) crossing the Solar System could be also a unique way to study origins and formation of objects outside the Solar System by studying the reflected light.

Questions still open that future missions should focus on are What is the effect of the solar wind on the texture and composition of the surface of the Moon and other objects? What depth is affected by this interaction and is it possible to infer the presence of a magnetic field from surface properties? Why are the lunar PSRs highly porous? What is the amount and composition of gas trapped at the surface of the icy satellites and how it is produced? What is the composition and the structures of the ices and organics at the surfaces of KBOs and comets?

2.2 Planetary atmospheres

As for planetary surfaces, a large set of information on planetary atmospheres can be deduced from UV observations by different methods (atmospheric emissions, occultation, ...). These different methods provide information on the composition and chemistry, energy budget, dynamics, haze and aerosols content of the planetary atmospheres and their spatial/temporal variations at different scales. In this section, we will not present an exhaustive list of all research areas that could benefit from new UV observations from Earth with high performance, but only focus on a few examples of current active research.

2.2.1 The atmospheres of Mars and Venus

The atmospheres of Mars and Venus have been extensively studied from spacecraft. However, there are several processes that remain unknown for both planets. On Venus, the origin of the dark UV regions, which were first reported in 1927 [29], is still unanswered, despite a large amount of observations of these dark regions [30]. The substance responsible for the absorption is still unknown even if several candidates (e.g., sulfur dioxides, iron chlorides) have been proposed [31, 32]. Its spatial distribution is also not understood and could be due to chemical effects or dynamical effects inside the cloud layers. The cloud structure from 30 km to 70 km could be formed from three layers: haze, aerosols, and gas, with different thicknesses for the bright and dark regions, but it needs to be confirmed. Finally, the lower cloud layer on Venus has been suggested as a potential region favorable for microbial life [33], which strengthens the interest to better define the concept of "habitability" inside the Solar System.

On Mars and Venus, the current D/H ratios suggest a large amount of hydrogen loss during their history. In order to estimate the amount of water loss and their atmospheric evolution along their history, a full understanding of the D/H fractionation is needed. Recent UV observations have shown an unexpected large coupling between the lower and upper atmosphere, affecting the water escape and the D/H ratio in the Martian upper atmosphere [34, 35]. The origin of this coupling is not known in detail but could be attributed to an extension at high altitudes of dust and water vapor [36]. An accurate vertical profile of aerosols and composition would be required to better understand the origin of this coupling. Such coupling could even extend to very high altitude inside the induced magnetosphere of Mars, and change the structure of the interaction with the solar wind [37]. Unfortunately, the sensitivity of the echelle mode of MAVEN/IUVS is not sufficient to measure the deuterium Lyman-α emission along the full Martian orbit but only near the southern summer season, when the deuterium brightness becomes larger than 100 R and only a few detections of deuterium emission have been obtained at other seasons [38]. H_2 is another important species needed to understand the full cycle of hydrogen that has been observed only one time by HST [39] due to its very weak UV emission. It would need to be redetected to validate the current scenarios of water escape. On Venus, the D/H ratio is even larger than on Mars, but the atomic deuterium abundance in the upper atmosphere is not known. Contrary to Mars, on Venus due to its larger gravity, the Jeans escape is negligible and non-thermal processes are present to produce the hot hydrogen population observed from UV measurements by Venus Express [40] and able to escape. These processes should also create a hot deuterium population able to escape [41]. This hot deuterium population has never been detected. Its measurement should be important to interpret the D/H measurements and estimate the amount of water escape on Venus along its history. The interaction of the Venusian atmosphere with the solar wind could also produce the unexplained periodicities of the UV dayglow observed by Hisaki/EXCEED [42].

Questions still open for Venus and Mars atmospheres are What is/are the unknown UV absorber of Venus, what is the detailed vertical structure inside the cloud layer on Venus? What are the present and past escape rates of D and H on both planets and what are the drivers of the temporal variations of their dayglow emissions?

2.2.2 The atmospheres of titan and Pluto

Titan is the only moon in the Solar System with a thick atmosphere. Past observations done by Cassini-Huygens, Pioneer, Voyager 1 and 2, and Earth-based facilities have revealed a complex atmosphere dominated by N_2 and CH_4 and the presence of a large variety of organic molecules [43] and ions. These heavy ions could form the transition from small gas phase molecules to haze particles [44]. The thick and hazy atmosphere of Titan, is a natural laboratory of complex organic chemistry, possibly forming molecules of prebiotic interest. The presence of a water ocean under the surface and ethane/methane lakes at its surface and their interaction with the atmosphere is crucial to better define the concept of habitability and the conditions for life emerging in the Solar System and in other planetary systems [45]. The composition and the structure of the different haze layers, their spatial and temporal variations are not fully known and will require new observations to be understood.

The composition of Pluto's atmosphere has been inferred from Earth since its detection in 1988 [46]. It has been recently observed in detail during the New Horizons flyby on July 142,015, close to the Pluto perihelion (the Pluto-Sun distance was 32.9 AU), revealing a globally hazy atmosphere [47] and a different thermal structure than predicted based on Triton's atmosphere observations. Solar occultations performed by the Alice UV instrument provided vertical profiles of several species: N_2, CH_4, C_2H_2, C_2H_4, C_2H_6, and haze [48] and a cooler atmosphere than predicted before New Horizons (and therefore a much lower Jeans escape rate for N_2 and CH_4). Like the atmosphere of Titan, the atmosphere of Pluto is chemically complex and the haze in the atmosphere of Pluto, observed at high altitudes, is structured in several thin layers and not spatially uniform. It presents a larger extinction in the northern hemisphere than the southern hemisphere [49]. The origin of the different layers, the size of the particles of the different layers are new questions raised by the New Horizons flyby that need new observations to be fully answered. Properties of the haze has started to be deduced from these observations, but they only represent the state of the atmosphere of Pluto at one given time. The atmosphere of Pluto is very variable due to condensation/sublimation at the surface along its orbit around the Sun. In order to understand its long term evolution and to compare with the possible atmospheres of other KBOs, or to make comparison with the similar atmosphere of Titan, new systematic UV observations are needed.

Questions still open for the atmosphere of Pluto and Titan are What is the composition and the structure of the haze in the different layers and what are their spatial and temporal variations?

2.2.3 Cometary atmospheres

N_2 is an important tracer of the physical conditions prevailing at the time of comet formation. The recent discovery of N_2 in the Jupiter-family comet 67P/Churyumov-Gerasimenko (hereafter 67P) by the mass spectrometer ROSINA on-board Rosetta [50], offers also a good opportunity to search for this species in the UV range (even if N_2^+ can also, only in a very few cases, be observed in the optical range). The Rosetta/Alice UV observations revealed a different environment in the low activity 67P comet, driven by electron impact rather than photochemistry and resonant scattering [51]. The electrons are probably photoelectrons accelerated to several eV but the acceleration processes are not known. The detection of O_2 from ROSINA and Alice [26, 52] on 67P was unexpected since O_2 had never been observed in any comets before. The reanalysis of Giotto's data, indicating the presence of O_2 in 1P/Halley [53], suggest that O_2 could be common on comets. Several mechanisms have been suggested to explain its formation. It could be of primordial origin before the formation of the comet and would have been preserved during the formation of the comet or it could have been formed after the formation of the comet by in-situ processes [54].

Question still open are What are the physical conditions of cometary grains formation? What is the origin of O_2? Is O_2 present on all comets and what is the variability of O_2/H_2O for the different comets? What is the N_2 fraction in the different comets?

2.2.4 The Lyman-α bulge at Jupiter

In the equatorial region of Jupiter, a Lyman-α enhancement ("Lyman-α bulge") has been detected independently with the International Ultraviolet Explorer (IUE) [55] and the Ultraviolet Spectrograph (UVS) [56] between System III longitudes 60–120°. High spectral observations of this region suggest that the increase of the brightness is not due to a larger hydrogen abundance but to a larger linewidth possibly due to a Doppler broadening due to winds or to the presence of a small hot population. This bulge has been observed by Cassini during its flyby of Jupiter, confirming a long-lived structure [57]. The observed correlation between the brightness of the bulge and the solar flux supports a resonant scattering mechanism but the origin of the bulge is still not known.

Question still open are What is the origin of the equatorial Lyman-α bulge observed on Jupiter and its temporal variability?

2.3 Planetary magnetospheres and auroral emissions of giant planets

The auroral emissions are emissions produced by extra-atmospheric energetic particles interacting with an atmosphere. They have been observed on the four giant planets and even if the mechanisms are similar, each planet is unique due to its unique source of external plasma and magnetosphere.

The ultraviolet aurorae were observed on Jupiter in 1979 and Saturn in 1980, 1981 by the Voyager 1 and 2 spacecraft during their flybys. Later, several observations, especially from the Hubble Space Telescope imaged the auroral regions of Jupiter and Saturn with a high spatial resolution showing numerous distinct auroral features, including the main oval, the polarward emissions, the diffuse equatorward emissions, and the satellite footprints. On Jupiter, the main oval is relatively stable, with temporal variations associated to both internal (Io volcanoes) and external (solar wind) drivers [58]. It is thought to be produced by upward field-aligned current inside the Jovian magnetosphere [59]. The polar emissions are much more rapidly variable and covered both closed and open field regions [60].

On Saturn, the main oval is variable (e.g. [61, 62]) and generated by upward field-aligned currents flowing along the magnetic field lines near the boundary between the closed and the open field lines and therefore more sensitive to solar wind conditions than the Jupiter's main oval [63]. Secondary emissions of interest also include diffuse equatorward emission, polar spots and an auroral footprint linked to the Enceladus moon.

On Uranus, UV auroral emissions were identified by Voyager 2 and have been re-detected and imaged by HST after several years of unsuccessful attempts. The emission has extended spots rotating with Uranus, interpreted as polar cusp aurorae assigned to the variable solar wind/magnetosphere geometry. These auroral features could also be used to constrain the position of the magnetic poles [64, 65].

Only weak UV emissions were detected on Neptune during the Voyager 2 flyby [66]. The precipitating particles could come from the internal magnetosphere (Triton torus) or from the solar wind.

The giant planets' UV aurorae are mainly radiated from atmospheric H and H_2 species, collisionally-excited by accelerated charged particles precipitating along the auroral magnetic field lines. Aurorae thus directly probe complex interactions between the ionosphere, the magnetosphere, the moons, and the solar wind [67, 68]. The energy of the precipitating electrons can be derived from partial spectral absorption of H_2 emissions by hydrocarbons [69, 70] using the color ratio (CR) of I(155-162 nm)/ I(123-132 nm). The energetic electrons can penetrate deeply in the atmosphere where the absorption of the H_2 emissions at wavelengths $\lambda < 140$ nm by CH_4 is important. The color ratio is therefore large (~10 20). The less energetic electrons excite molecules at higher altitudes where no absorption by CH_4 occurs and the color ratio is low (~ 2). When assuming a model atmosphere, the CR method can thus be used to directly map the energy distribution in the Jovian auroral regions [60]. Another method, based on the brightness ratio of H Lyman-alpha to H_2 bands [71], has been used to directly probe low energy electrons with limited penetration depths. The CR and brightness ratio methods have been used together in a statistical manner to exhaustively study the electron precipitations associated to Saturn's various auroral components [69].

Precipitation of auroral particles is additionally a major source of atmospheric heating, whose knowledge is needed to assess the energy budget, the dynamics and the chemical balance of the atmosphere [72]. While few infrared measurements have been used to derive temperatures and ion winds, only an upper limit on the neutral winds has been estimated [73]. Few high spectrally resolved UV measurements of the Lyman-α line have been used to estimate the neutral hydrogen winds in polar regions [74, 75] showing large velocity of 4–10 km/s. More observations would be needed to better map the full dynamics of the Jovian upper atmosphere in the auroral regions.

Questions still open are: What is the heating and dynamics of the giant planets' upper atmosphere driven by the electron precipitations? What is the energy range of precipitating electrons on Uranus, and Neptune and can we estimate it for exoplanets? What are the temporal variations and the morphology of the aurorae on Uranus and Neptune?

3 How would a space mission address these scientific questions?

3.1 What to measure: Surface

The Moon is the better-known object without an atmosphere. Its surface has been observed at all wavelengths. Polarization of the incident unpolarized solar light was also used to infer unique information on the grain sizes of the surface [76]. Such observations would be useful for objects difficult to observe by spacecraft because of their large number (asteroids from the main belt) or their distance to Earth (KBOs). The

Moon's observation would be especially useful for calibration because the samples of its surface can be directly studied on Earth. For example, the effect of space weathering on the UV properties of the surface of the Moon studied by the Lunar Reconaissance Orbiter [18] could be used to estimate the time of exposition of a surface to an incident plasma or to detect, in the future the presence of a magnetosphere on exoplanets without an atmosphere. UV observations of the Moon show a transition in the scattering near 220 nm with a scattering from grain surfaces for wavelength < 220 nm and volume scattering for wavelength > 220 nm [77]. Therefore, wavelengths below 220 nm are more sensitive to thin coating on grains resulting from weathering processes [18].

UV spectroscopy with imaging and polarimetric capability will be useful, not only to study transient events due to geological processes but also to study the composition and texture of the surface ices, their spatial variations, and the atmosphere bubbles trapped in them. Several UV spectral features can be used to study the composition of the surface of icy objects. For example, the strong absorption features of the albedo near 330 nm or near 180 nm are typical signatures of SO_2 ices and H_2O ices respectively observed at Io and Ganymede respectively, while iceless surfaces have a featureless UV spectra. For icy surfaces, UV features can also be due to the absorption by trapped gas ("microatmosphere") like the absorption near 260 nm in the reflected solar flux by the surface of Ganymede, Rhea, Dione, and Tethys due to O_3 in the surface ices [23, 24].

Imaging of the surfaces has been used in the past to study longitudinal variations of the surface reflectance showing leading/trailing asymmetry associated to the ion bombardement of the surface from magnetospheric heavy ions [78] and Jovian/anti-Jovian asymmetries associated to neutral or dust impact.

Organic and ice composition of the surface of comets, asteroids, and Kuiper Belt Objects can be studied from their surface UV spectrum. The UV spectral regime is important to assess the presence of carbon on primitive bodies such as C, B, and D asteroids and comet nuclei, since this element is nearly featureless both in the visible and in the IR, but in the UV, carbon, in various forms (amorphous, graphitized, hydrogenated, glassy), has a very important peak at 210–220 nm and an absorption signature at 80 nm.

When the solar unpolarized light is scattered by a rough surface or a dust covered surface of a solar system body, it becomes partially linearly polarized. At low phase angle, the polarisation is negative (parallel to the scattering plane) while at large phase angle, the polarisation is positive (perpendicular to the scattering plane) [79]. The variations of the polarisation with the phase angle curve is a signature of one surface, and has been used in the past to infer properties of the surfaces of Solar System bodies (e.g. [76]). It is therefore another useful tool to characterize surface properties. Numerous polarimetric observations of Solar System bodies have been done in the optical spectrum but very few at UV wavelengths were obtained so far. For example, the Wisconsin Ultraviolet Photopolarimeter Experiment (WUPPE) observations of Io have revealed a surface spatially covered by 25% SO_2 frost with polarization variations associated to different volcanic regions [80]. Observations of the Moon show a transition in the scattering of the UV light near 220 nm with a scattering from grain surfaces for wavelength < 220 nm and volume scattering for wavelength > 220 nm [77]. Such processes have been studied in the past to explain the change of polarisation with phase angle at visible wavelength (e.g. [81]) but systematic observations of the

UV polarisation of the surface of different objects in the Solar System could open a new field of investigation to constrain the surface properties (refractive index, surface roughness, particle size). Remote measurements of the surface properties of the objects of the Solar System could be validated/calibrated in the future and then be used to study surface properties of exoplanets or, interstellar objects (like Oumuamua) that cannot be reached by spacecraft.

3.2 What to measure: Atmospheres

High spectral UV spectroscopy and UV polarization observations would help to identify the Venusian unknown absorber and its spatial distribution and variations. The identification of the sulfuric acid composition of Venus' cloud particles was derived from polarization measurements at different wavelengths, by constraining the index of refraction, to fit the phase dependence [82]. UV polarization has been measured at a few wavelengths by the Pioneer Venus Orbiter for different phase angles showing a contrast in the polarisation of the dark regions and the bright region of the atmosphere of Venus [83] and the Rayleigh optical thickness and haze optical thickness deduced from a fit with a three layers model. The full UV spectrum at high spectral resolution coordinated with spectral imaging of Venus could be used to derive new information on the unknown absorber responsible of the dark UV regions (e.g. [31]). Such studies could be extended to other objects with a thick atmosphere like gas giants and ice giant planets, although the phase curve will be limited for an observer near Earth.

Simultaneous UV observations of the lower and the upper atmosphere of Mars would be required to better estimate the timescales of this coupling and derive the vertical variation of the D/H ratio in the Martian atmosphere. High spectral resolution able to separate the deuterium and hydrogen Lyman-α line with high sensitivity could allow a derivation of the D/H ratio along the full Martian orbit.

The UV polarization would be a unique tool to investigate the aerosol sizes. Indeed, several processes can polarize the light in planetary atmospheres: Rayleigh diffusion by molecules and small particles, hazes, aerosols, etc. The Rayleigh scattering cross section varies as $\sim 1/\lambda^4$ while the scattering by aerosols is less dependent on the wavelength. Therefore, the Rayleigh scattering is generally dominant at short wavelength while aerosol scattering is dominant at large wavelength in the UV range. The transition between the two processes depends on the size of aerosols and the pressure. On Mars, at a phase angle $V = 21.7°$, the linear polarized reflected light in the spectral range 200–400 nm is due to the atmosphere, while the reflected light in this spectral range is due to the surface and the atmosphere [84] (Fig. 1).

Therefore, the combination of both can be used to derive simultaneously the UV albedo of the surface and the atmosphere as done in the past from the WUPPE observations. From these observations, the surface pressure of Mars was derived. These observations prove that polarized observations of other Solar System bodies with a tenuous atmosphere, like Ganymede, Pluto, Triton, etc., will be useful to study the aerosol content and atmospheric pressure and its composition. On Venus, because of the thick atmosphere, the polarisation is only due to the atmosphere.

For Pluto and Titan, such observations could provide information on the size of the aerosols forming the haze in the atmosphere. Moreover, observations at different times

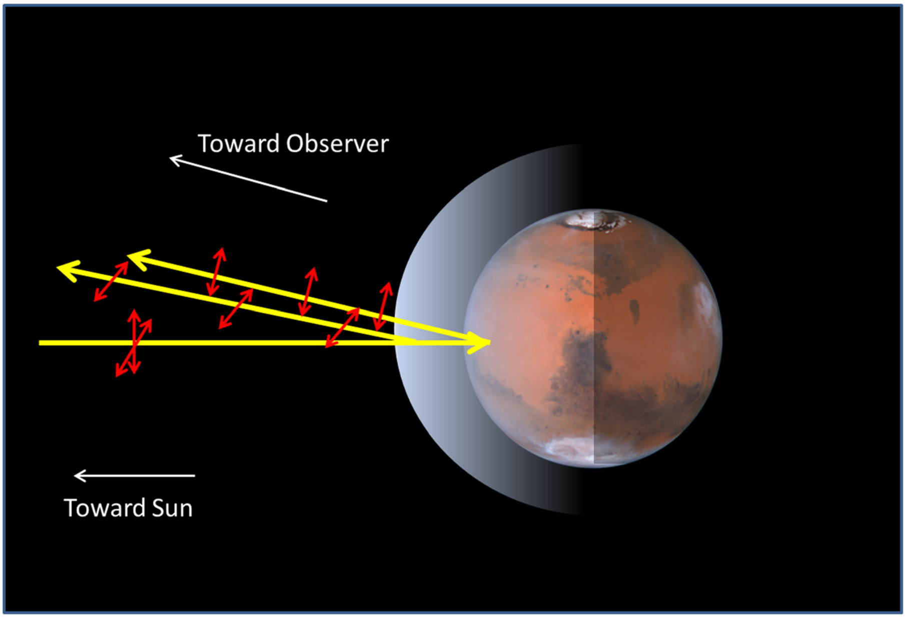

Fig. 1 Example of UV polarimetric observations for an optically thin atmosphere like Mars at low phase angle (based on [84]). Between 200 nm and 400 nm, the unpolarized sunlight can be scattered by the atmosphere (Rayleigh scattering and aerosols) and the surface. The linear polarization $P(\lambda) = (I_{perpendicular}(\lambda) - I_{parallel}(\lambda))/(I_{perpendicular}(\lambda) + I_{parallel}(\lambda))$ is mostly due to the atmosphere, while the total reflected light: $I_{perpendicular}(\lambda) + I_{parallel}(\lambda)$ is due to the surface and the atmosphere

could help to understand how the atmospheres of Pluto and Titan evolve along their orbits around the Sun and if some short term atmospheric global motions can affect their atmospheres. For Pluto, the expected large variations of the surface pressure with time could also be deduced from this UV polarimetric observations if the sensitivity is large enough.

Studying the atmospheres of the objects of the Solar System from Earth-based observations is also needed to calibrate and interpret observations of exoplanet atmospheres. Numerous exoplanets have an aerosol absorber in their atmospheres, and because exoplanets will not be accessible to spacecraft in the near future, only observations from remote sensing will provide information on their atmospheres. To derive solid interpretation of these observations, especially on the haze structure, composition, variations, etc., systematic study of the atmospheres of the Solar System objects with the same method will be required.

Independently of polarimetric observations, spectroscopy in the UV range permits the detection of a large number of lines corresponding to many atomic or molecular species observed in the gas phase. It is especially true for cometary atmospheres where the UV spectral range corresponds to several interesting molecular / atomic species in the cometary coma / tails. We can mention CO, OH, H_2, CS_2, CS, H, C, N, S, O, CO^+, and CO_2^+. For OH and CO isotopic ratios can be derived, especially D/H with OH (emission lines at 309 nm). UV stellar occultations by other comets from Earth-based observations in the next years could be done to check if the O_2 is present in all comets.

3.3 What to measure: Magnetospheres

A highly sensitive UV spectro-imager will measure the complex aurorae of Jupiter and Saturn, the fainter ones of Uranus, and catch those of Neptune, only seen by Voyager 2 [85]. Orbiters around both Neptune and Uranus are costly. UV observations from a space telescope at L2 Lagrange point, with a large aperture telescope and high spatial resolution could detect their auroral emissions and search for permanent structures as observed on Jupiter and Saturn and would be a good option to compare these two icy giant planets.

A spectrometer with a high spectral resolution will be used to finely map the energy of precipitating electrons from partial spectral absorption of H_2 by hydrocarbons [69, 70] and the thermospheric wind shear from the H Lyman-α line [74]. The measurement of the linear polarization induced by the Hanle effect on the Lyman-α line could provide a way to measure the magnetic field at the "surface" of Jupiter (near 1 bar), at altitudes never observed before [86].

Finally, highly sensitive observations of the temporal variations of the auroral structures (oval or bright spots) of the Jovian moons like Ganymede and Io can be used to constraints their conductive layer (thickness, conductivity) below their surface [87, 88]. Such a method is more difficult to use for a rather patchy auroral structure as observed on Europa [89], but spectro-imaging with a better sensitivity could help to extend this method to Europa and provide constrain on the conductivity and then, ion concentration of its water ocean, possibly linked with the surface plumes.

4 A new multi-object UV observatory

The planned termination of the highly successful Hubble Space Telescope (HST) will prevent scientific UV observations of the Solar System at large aperture with high spectral resolution. This telescope has provided numerous discoveries about surfaces, atmospheres, and magnetospheres of the different objects of the Solar System that need to be extended to answer all the questions arising from these past observations. A new multi-object UV observatory at the Sun-Earth L2 point would be needed to study the different objects of the Solar System. The Sun-Earth L2 Lagrange point has several advantages: it is far enough from Earth to avoid UV contamination by the geocorona, it provides a stable thermal environment, a good field of regard, and ease the communications with Earth and the possibilities of coordinated observations in infrared with the James Webb Space Telescope (also at L2). Some continuous UV surveys of the Solar System objects would be needed to answer some questions mentioned in the previous section even without a larger ability than the Hubble Space Telescope. The UV range from 80 nm to 400 nm would be the nominal range where a large number of strong resonance lines are present. The highest needed spectral resolution would be to separate the D and H Lyman-α spectral (0.33 Angstroms), requiring a spectral resolution larger than ~4000.

A UV spectro-imager would be required to map the surfaces, atmospheres, and auroral regions of the different objects of the Solar System. A UV spectropolarimeter would be needed to provide measurements on the surface texture, atmospheric aerosols, surface pressure for KBOs, and magnetic field measurements from the Hanle effect. One major challenge in the UV observations of small bodies (KBOs, comets, and other faint emissions from icy moons) is the sensitivity. This sensitivity will be directly dependent on the aperture size of the telescope and will constrain the mass of the telescope and the class of the mission.

To illustrate the effect of the aperture on one of the scientific goal presented above, we estimate the size of an observable object as a function of its distance to the Sun, assuming an albedo between 260 and 310 nm equal to 0.5 and considering a UV efficiency close to COS [27]. This is shown in Fig. 2, assuming a detection for a signal to noise ratio equal to 10 (neglecting instrumental biases) and an integration time of 600 s for different values of the aperture diameter. The smallest KBOs observed in UV with HST (aperture diameter = 2.4 m) are the moons of Haumea: Namaka (mean radius ~ 155 km at 50.95 AU) and Hi'iaka (mean radius ~ 85 km at 50.95 AU). Numerous other KBOs and Centaurs with radii larger than 300 km can be observed in UV at distances lower than 50 AU with an aperture of 1.5 m, and until 180 AU with a 15 m diameter aperture. This would largely increase the statistics of UV observations of KBOs and their possible surface activity variations along their orbit around the Sun.

5 Conclusion

The UV observations performed in the past years, particularly from spacecraft and from the Hubble Space Telescope, have provided a unique and large amount of information

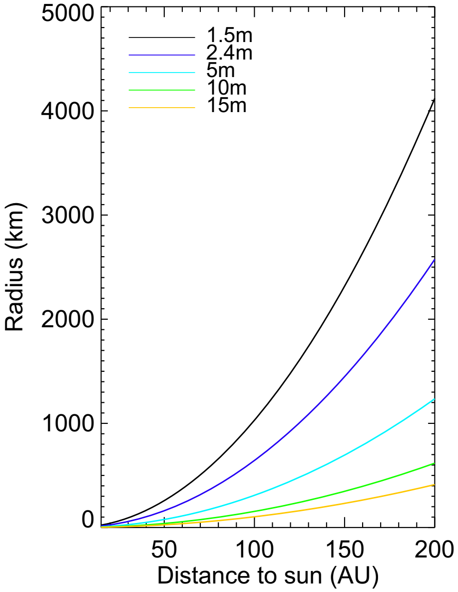

Fig. 2 Minimal radius of the observable KBOs as a function of the distance to the Sun, to have a count rate of 100 for 10 min of observation, assuming the instrumental efficiency of HST/COS and a Lambertian albedo of 0.5 in the 260–310 nm spectral range, for different telescope aperture diameter

on surfaces, atmospheres, and magnetospheres of the Solar System objects. These observations have also opened new questions that could be solved by improved observations (sensitivity, spectral resolution, polarimetry) and/or a larger temporal coverage. In this White Paper, we have presented a few examples of major science that should be studied thanks to the higher sensitivity and new techniques (polarization) from the next generation of UV telescope. The planned termination of the Hubble Space Telescope in the near future will prevent such continuous observations of multiple objects needed to understand how the Solar System works and to interpret the observations of exoplanets. Therefore, as shown in this White Paper a new multi-object UV observatory is needed to answer the major questions presented above and to open new possibilities of exploration in the Solar System.

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