UV Exploration of the solar system (Astro2020 Science White Paper)

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Astro2020 Science White Paper

UV Exploration of the solar system

Thematic Areas: ☒ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract (optional):

1) Introduction

The study of the solar system is fundamental to answer key questions from the NASA Strategic Plan Objective 1.5: "Ascertain 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 to this objective from the surface to the atmosphere and magnetosphere of the solar system bodies. The UV measurements of the surface albedo and polarisation can provide information on the surface activity (volcanisms, plumes), its composition in water ices / organic matter and its texture (particule size, roughness, ...). The 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 future. Finally, UV studies (for example from 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 giant ices planets (Uranus and Neptune) and used to interpret possible weakest detection of exoplanets auroral emissions. In this white paper, we will summarize few examples of the major science results that could be obtained from future UV measurements of surfaces (section 3), atmospheres (section 4) and magnetosphere (section 5) for different objects in the solar system.

2) Planetary Surfaces

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 (Hendrix et al. 2012). For example, UV emissions associated to the plume activity from the surface of Europa (Roth et al. 2014) has been detected from Hubble Space Telescope (HST). This activity could be due to tidal stress opening and closing fractures at the surface, but the frequency of this activity is still unknown and new observations are required to confirm this theory. UV emissions from the Io plasma torus, produced from Io volcanoes can be used to study the effect of the volcanic activity at the Io surface on the Jovian magnetosphere (Mendillo et al. 2004, Yoneda et al. 2015). UV spectroscopy with imaging and polarimetric capability will be useful, not only to study transient event 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 is a typical signatures of SO_2 ices and H_2O ices observed at Io and Ganymede respectively, while iceless surfaces have a featureless UV spectra (Hendrix et al. 2012). 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, Tethys due to O_3 in the surface ices (Noll et al. 1996, 1997). Knowing the composition of the surface ices and trapped gas is important to better understand the chemistry induced by surface sputtering (Johnson and Jesser 1997). 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 (Johnson et al. 1988) and jovian/anti-jovian assymetries associated to neutral or dust impact.

The determination of the surface composition of primitive bodies in the solar system is fundamental to understand the origins and formation of the planets. Organic and ice composition of the crust of comets, asteroids, Kuiper Belt Objects (KBOs) 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, D asteroids and comets 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) (Geake et al. 1984). 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. Geake and Dollfus 1986). 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 has revealed a surface spatially covered by 25% SO_2 frost with polarization variations associated to different volcanic regions (Fox et al. 1997a). Observations of the Moon show a transition in the scattering of the UV light near 220 nm with a scattering from grains surface for wavelength < 220 nm and volume scattering for wavelength > 220 nm (Fox et al. 1998). Such processes have been studied in the past to explain the change of polarisation with phase angle at visible wavelength (e.g.Steigmann et al. 1978) but systematic observations of the UV polarisation of the surface of different objects in the solar sytem 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, interstellar objects (like Oumuamua) that can not be reached by spacecrafts.

3) Planetary Atmospheres

Several processes can polarize the light in planetary atmospheres: Rayleigh diffusion, hazes, aerosols, etc. The Rayleigh scattering cross section varies as $\sim 1/\lambda^4$ while the scattering by aerosols varies as $\sim 1/\lambda$. Therefore the Rayleigh scattering is generally dominant at short wavelength while aerosols scattering is dominant at large wavelength in UV range. The transition between the two processes depends on the size of aerosols and 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 (Fox et al. 1997b) (Fig. 1).

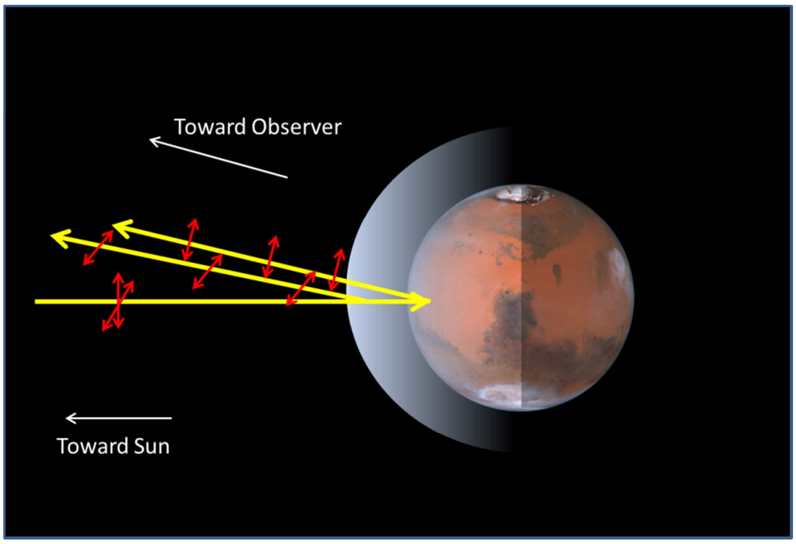

Fig. 1 Example of UV polarimetric observations for an optically thin atmosphere like Mars at low phase angle (based on Fox et al. 1997b). Between 200 and 400 nm, the sun unpolarized can be scattered by the atmosphere (Rayleigh scattering and aerosols) and the surface. The linear polarization $P(\lambda) = (I_{perp}(\lambda) - I_{para}(\lambda))/(I_{perp}(\lambda)+I_{para}(\lambda))$ *is mostly due to the atmosphere, while the total reflected light :* $I_{perp}(\lambda)+I_{para}(\lambda)$ *is due to the surface and the atmosphere.*

Therefore, the combination of both can be used to derive simultaneously the UV albedo 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 bodies with tenous atmosphere in the solar system like Ganymede, Pluto, 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. It has been measured at few wavelengths by Pioneer Venus Orbiter for different phase angle showing a contrast in the polarisation of the dark regions and the bright region of the atmosphere of Venus (Esposito and Travis 1982) 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. Frandsen et al. 2016). Such studies could be extended to other objects with a thick atmosphere like gas giants and ice giants planets, although the phase curve will be limited for an observer near Earth.

Independantly of polarimetric observations spectroscopy in the UV range permits to detect 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^+, CO_2^+. For OH and CO isotopic ratios can be derived, especially D/H with OH (emission lines at 309 nm). The recent discovery of N_2 in comet 67P by the ROSINA instrument on-board Rosetta (Rubin et al., 2015), an important tracer of physical conditions prevailing at the time of comet formation, 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 (Feldman et al., 2018). Such observations open also a new field of investigations for an instrument observing in the UV.

Instruments with high sensitivity will observe the tenuous atmospheres that should be present around small bodies like Ceres. Search for UV atomic emission lines (H, O, S) in the exosphere of Ceres have been done with HST but no detectable emissions have been observed (Roth 2018). Such detections could be important to know if there is a persistent exosphere around Ceres or only a transient exosphere associated to enhancements of the solar wind flux (Schorgofer et al. 2017).

4) Planetary magnetospheres and Auroral emissions

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 (Clarke 2004). Aurorae can be used to understand the energy transport and dissipation through the giant magnetospheres (Bhardwaj and Gladstone 2000). 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 (Majeed et al. 2009). A high sensitive UV spectro-imager will measure the complex aurorae of Jupiter and Saturn and, the fainter ones of Uranus and catch those of Neptune, only seen by Voyager 2 (Lamy et al., 2017). 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 (Ménager et al. 2010, Gustin et al., 2017) and the thermospheric wind shear from the H Lyman-α line (Chaufray et al. 2010). 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) (BenJaffel et al. 2005).
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 constrain their conductive layer (thickness, conductivity) below their surface (Saur et al. 2015, Roth et al. 2017). Such a method is more difficult to use for a rather patchy auroral structure as observed on Europa (Roth et al. 2016), 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 observed (see section 2).

Conclusion

The UV spectral range is a crucial window to investigate a large area of phenomena associated to the surface, the atmosphere and the magnetosphere of the solar system bodies.
In this white paper, we have presented 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 (e.g.. LUVOIR) that will open new possibilities of exploration in the solar system.

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