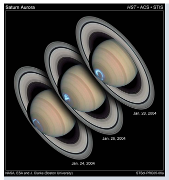

# UV Imaging Spectroscopy: The 2050 Vision

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## Introduction/Overview:

Ultraviolet (UV) imaging spectroscopy has proven to be an invaluable technique for planetary science studies, and in the last decades has demonstrated its diverse potential for planetary science discoveries. We encourage the community to support use of this technique as we continue on our journeys in the solar system to 2050, even to targets not traditionally thought of as being sources of UV signals. It is also critical that UV-related technologies are advanced and laboratory studies are encouraged, to continue furthering the scientific results of these instruments at other planetary bodies.

## New insights in the last decade:

- UV spectroscopy has been used since the earliest space missions for atmospheric and auroral studies (e.g. [2][3][4][5][6][7][8][9]). UV spectroscopy for studying cometary emissions is also well-established (e.g. [13]). The lunar exosphere was studied in the UV in the Apollo 17 mission [14] and study continues with the LRO/LAMP investigation (e.g. [15]).

- A number of UV instruments have flown or are flying on spacecraft (e.g. Hubble Space Telescope (HST), Lunar Reconnaissance Orbiter (LRO), Cassini, Rosetta, MAVEN), and more will do so in coming years. These UV instruments are enabling significant new findings regarding surfaces and plumes/thin atmospheres.

- Insights from UV imaging spectroscopy of solar system surfaces have been gained largely in the last 1-2 decades, including studies of surface composition, space weathering effects (e.g. radiolytic products) and volatiles on asteroids (e.g. [1][16][17][18][19]), the Moon [20][21][22], comet nuclei [23] and icy satellites (e.g. [24][25][26][27][28][29][30]). The UV is sensitive to some species, minor contaminants and grain sizes often not detected in other spectral regimes. **Figures 1-6 below.**

- The advantages of UV imaging spectroscopy for detecting and investigating plumes and thin atmospheres (e.g. at Enceladus, Io, Europa) via emissions and occultations (gas absorptions) have been made obvious in recent years (e.g. [10][11][12]). **Figures 7-10 below.**

## SURFACES: ICY AND NON-ICY

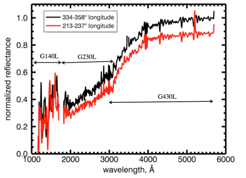


**Figure 1.** Ceres: composite normalized reflectance spectra measured using HST/STIS on two hemispheres on Ceres. The UV absorption edge near 4000 Å is interpreted as due to phyllosilicates plus sulfur species; the "bump" near 1600 Å is due to graphitized carbon. From [1].

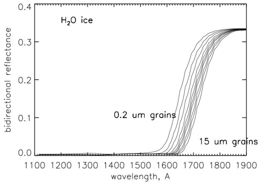


**Figure 2.** The UV reflectance spectrum of water ice of varying grain sizes; models from [26]. Other ices also have strong, diagnostic absorption in the UV.

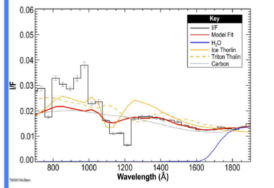


**Figure 3.** The reflectance spectrum of comet 67P/Churyumov-Gerasimenko as measured by Rosetta Alice. From [23].

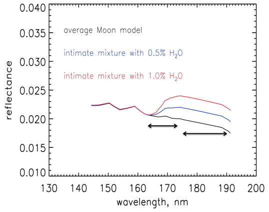


**Figure 4.** Simulations of intimately-mixed lunar regolith with varying small amounts of $H_2O$ to demonstrate spectral slope change in the 164-173 nm range due to small amounts of hydration in the dayside lunar regolith. From [21].

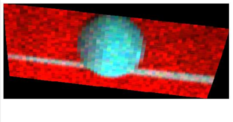


**Figure 5.** Far-UV image of Rhea from Cassini UVIS. Red=Lyman alpha; blue/green= 1600-1880 Å.

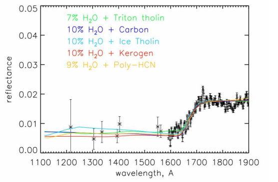


**Figure 6. A Cassini UVIS spectrum of Phoebe** shows the strong H2O ice absorption edge at 1650 Å, mixed with a darker material. From [26].

## PLUMES AND THIN ATMOSPHERES

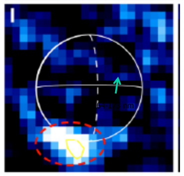


**Figure 7. A plume on Europa?** HST/STIS image of Ly-a (1216 Å) emission off Europa's south pole**.** From [11].

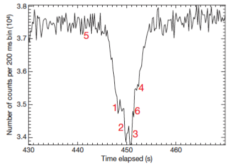


**Figure 8. Enceladus plume stellar occultation** as measured by the Cassini UVIS High Speed Photometer. Red numbers correspond to regions at the south polar, mainly (except #5) plume jets exhibiting enhanced gas absorption. From [32].

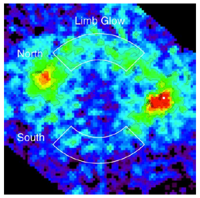


**Figure 9.** HST/STIS image of Io's OI] 1356 Å bright equatorial auroral emissions. From [31].

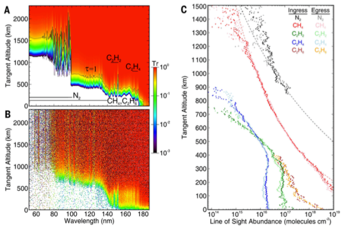
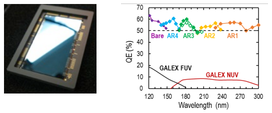


**Figure 10.** Ultraviolet transmission of Pluto's atmosphere as measured by New Horizons Alice (model in A, compared to data in B, includes absorptions by $N_2$, $CH_4$, $C_2H_2$, $C_2H_4$, and $C_2H_6$). From [33].

## Lab Work & New Technologies Needed:

As planetary science advances toward 2050, advancements in UV-related technologies (detectors, gratings, electronics miniaturization) are needed to advance to the next step. Weak signals at outer solar system targets (e.g. KBOs, Trojan asteroids, moons of Uranus and Neptune), for instance, will require utilization of more sensitive detectors to fully take advantage of the UV-diagnostic spectral clues. We also suggest that orbital missions are not the only place for UV instrumentation – landers and rovers can also benefit from this technology, for *in situ* studies.

Solid-state based ultraviolet technologies have been developed (e.g. [34]) that offer high UV efficiency, high spatial resolution, red rejection, and photon counting. These detectors have shown increase in the quantum efficiency x5 in the NUV and x2 in the FUV (**see right**). The enhanced performance is achieved through JPL's 2D-doping technology (delta doping and superlattice doping) applied to e2v's electron multiplying charge coupled devices (EMCCDs) with custom coatings (including red rejection filters) using atomic layer deposition (ALD). It is critical that these detectors are *flown* in space in the coming years, to improve performance at target bodies.



From [34]

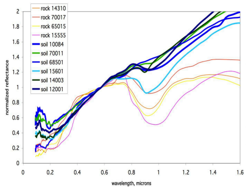


**Figure 11.** Lunar sample reflectance spectra (normalized) from [17], using data from [37]. These data provide critical insights into the UV responses to weathering (i.e. in lunar soils vs lunar rocks) as compared with longer wavelengths. **These are the only existing UV reflectance spectra of lunar samples** – more are needed to better understand these characteristics.

Furthermore, **UV lab studies** (e.g. reflectance spectra of candidate species and mixtures) are critically needed to support and interpret the acquired spacecraft data, down to wavelengths as short as ~100 nm (or shorter). The UV is an area that is seriously lacking in current spectral libraries. Some of the only existing far-UV lab data were made decades ago [37] of terrestrial, lunar, meteoritic powders, and frosts (including $H_2O$, $CO_2$, $SO_2$, and $NH_3$); their results suggest that extending the spectral range of lab measurements from the more traditional visible-NIR (VNIR) into the far-UV (100-200 nm) reveals significant diagnostic compositional information (e.g. **Fig 11**). UV lab measurements have particular challenges, but as evidenced by the newly identified carbon features, numerous discoveries can be anticipated in the next 30 years. Examples of needed lab data would seek to understand the lunar hydration signature (**Fig. 4**), the UV absorption in low-albedo class asteroids (e.g. **Fig. 1**) and carbon- and organic-rich bodies such as comet nuclei (e.g. **Fig. 3**) and KBOs (**Fig. 6**)***. Lab work in the UV is an area ripe for study in the coming decades.***

## Potential in the Coming Decades:

UV instrumentation on missions to Ice Giants, Ocean Worlds, Primitive Bodies and other destinations in the solar system will substantially enhance the science return from the missions by enabling plume/activity searches/detection, uniquely contributing to surface composition and volatiles studies and allowing investigations of aurorae and the upper atmospheres of ice giants. The potential is great!

MAVEN/IUVS at Mars is a prime example that improved instrumentation can result in substantial discoveries even ~50 years after the first interplanetary UV instruments.

*… Just think what can be accomplished in the next 30-50 years !!*

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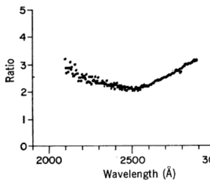
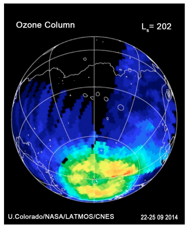


Discovery of ozone in Mars' atmosphere by the UVS on Mariner 7 (Barth & Hord, 1971).



MAVEN IUVS image of ozone in Mars' polar region.

**References.** [1] Hendrix, A.R. et al. (2016) *Geophys. Res. Lett.* 43, doi:10.1002/2016GL070240. [2] Barth, C.A. et al. (1971) *Planetary Atmospheres,* ed. Sagan et al. 253-256. [3] Stewart, A.I.F. et al. (1979) *Science* 203, 777-779. [4] Stern, S.A. (1996) *Icarus* 122, 200-204. [5] Clarke, J.T. et al. *Astrophys. J.* 430, L73-L76. [6] Caldwell, J. (1977) *Icarus* 32, 190-209. [7] Barth, C.A. et al. (1972) *Icarus* 17, 457-468. [8] Bertaux, J.-L. et al. (2005) *Nature* 435, 790-794. [9] Clancy, R.T. et al. (1996) *JGR* 96, 12777-12783. [10] Hansen, C.J. et al. (2006) *Science* 311, 1422-1425. [11] Roth, L. et al. (2014). *Science* 343, 171-174. [12] Retherford, K.D. et al. (2007) *Science* 318, 237. [13] Feldman, P.D. et al. (2002) *Astrophys. J.* 576, L91-L94. [14] Feldman, P.D. & D. Morrison (1997) *Geophys. Res. Lett.* 18, 2105-2108. [15] Feldman, P. D. et al. (2012) *Icarus* 221, 854-858. [16] Roettger, E.E. and B.J. Buratti (1994) *Icarus* 112, 496-512. [17] Hendrix, A.R. and F. Vilas (2006) *Astron. J.* 132, 1396-1404. [18] A'Hearn, M. et al. (2010) *Planet. Space Sci.* doi:10.1016/j.pss.2010.03.005 [19] Stern, S.A. et al. (2011) *Astron. J.* 141, 199-201. [20] Gladstone, G.R. et al. (2012) *J. Geophys. Res.,* 117, doi:10.1029/2011JE003913. [21] Hendrix, A.R. et al. (2012) *JGR* 117. [22] Hendrix, A.R. et al. (2016) *Icarus* 273, 68-74. [23] Stern, S.A. et al. (2015) *Icarus* 256, 117-119. [24] Nelson, R.M. et al. (1987) *Icarus,* 72, 358-380. [25] Hendrix, A.R. & C.J. Hansen (2008) *Icarus* 193: 344-351 [26] Hendrix, A.R. & C. J. Hansen (2008) *Icarus* 193, 323-333 [27] Hendrix, A.R. et al. (2010) *Icarus* 206, 608-617 [28] Hendrix, A.R. et al. (2012) *Icarus* 220, 922-931 [28] Hendrix, A.R. et al. (2011) *Icarus* 212, 736-743 [29] Hendrix, A.R. et al. (1999) *J. Geophys. Res.* 104, 14169-14178. [30] Hendrix, A.R. & R.E. Johnson (2008) *Astrophys. J.* 687, 706. [31] Retherford, K. D. et al. (2003) *JGR* 108(A8), 1333, doi:10.1029/2002JA009710. [32] Hansen, C.J. et al. (2008) *Nature* 456, 477. [33] Gladstone, R. G. et al. (2016) Science 351 [34] Nikzad, S. et al. (2012) *Appl Optics* [37] Wagner, J. et al. (1987) Icarus 69, 14–28