EUV Studies of Solar System Objects: A Status Report

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EUV studies have contributed substantially to our understanding of the physical and chemical properties the Sun, planets, and their satellites. Although the spectroscopic data set is limited to Venera 11/12, Voyager 1/2, Astro 1/2, EUVE, Galileo, and a handful of sounding rocket experiments, these data have provided important insights regarding the atmospheres and surfaces of several planets and satellites to the point where rudimentary comparative planetology can be conducted. In this paper we highlight some of these results.

1. Introduction

The EUV spectral region is rich in emission features from the most common planetary atmospheric species. Recently, it has also been proposed to be useful for studies of the surfaces of solar system bodies without atmospheres. Spectrographs aboard planetary spacecraft, most notably the Voyagers, have established the general EUV/FUV spectral characteristics of the upper atmospheres and plasma environments of most of the planets. The *EUVE* mission continues to provide new insights into solar system objects. The space-shuttle-based Astro missions and sounding rocket experiments have also added to our understanding of the solar system through their EUV observations.

The richness of the EUV spectral region for planetary studies has been discussed by Feldman & Bagenal (1991) (see their Table 1). Extreme ultraviolet emission features include transitions of atoms and their ions (e.g., H, He, He^+, Ne, Ar, O, O^+, O^{++}, N, N^+, N^{++}, S^+, S^{++}, S^{+++}) as well as molecules (e.g., H_2 and N_2). Through occultation studies, one can also infer the altitude distribution of abundant EUV-absorbing molecules (e.g., O_2 and N_2 on Earth, or hydrocarbons on the giant planets).

In this paper we provide a summary of EUV observations of solar system objects. The discussions will be broken into observations of the study of the Moon, the terrestrial planets, the jovian planets, the interplanetary medium, and comets.

2. The Moon

There have been only a small number of studies on EUV emissions from the Moon. An EUV spectrophotometer on the Mariner 10 spacecraft observed the Moon in the 550–1250 Å range and obtained a geometric albedo of 2–10% at a solar phase angle of 74°(Wu & Broadfoot 1977).

Prompted by the *ROSAT* soft X-Ray observation of the Moon (Schmitt et al. 1991), Edwards et al. (1991) simulated lunar EUV emissions from L- and M-shell X-Ray fluorescence. The authors predicted much higher emission peaks in the 90–500 Å range from this process than from the reflected solar spectrum.

During the all-sky survey phase of the *EUVE* operations, *EUVE* scanned the Moon on several occasions. Gladstone et al. (1994) used this data to estimate the solar EUV

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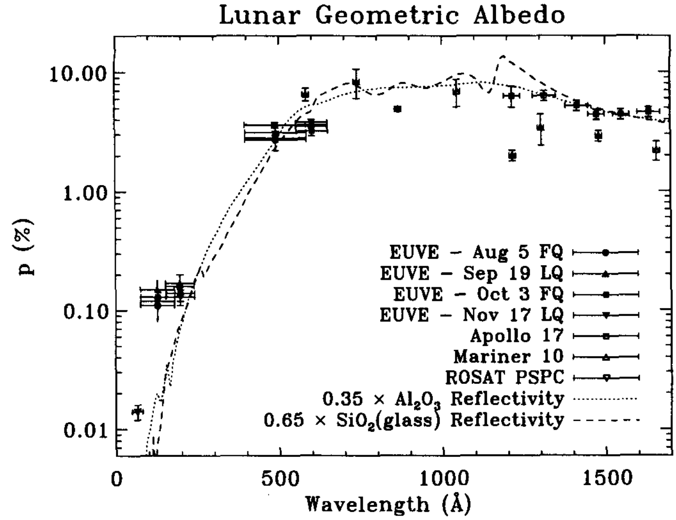

FIGURE 1. EUV albedo of lunar surface obtained by *EUVE* and other experiments.

irradiance and its variation. The authors used the bulk reflectivities of SiO_2 and Al_2O_3 (Phillip 1985 and Gervais 1991) to explain the photometric observations (Figure 1). The average geometric albedos obtained in the 150–650 Å range varied from 0.15% to 3.5% with an upper limit of 0.13% in the 75–180 Å range. The authors found that the primary features are consistent with reflected sunlight, rather than the X-ray fluorescence emissions suggested by Edwards et al. (1991). Subsequently, Gladstone (1994) used the *EUVE* spectrometer to obtain the EUV spectrum of the Moon, which indicated that the observed signal is primarily due to reflected sunlight.

3. Terrestrial Planets

Although there have been numerous EUV observations of Earth's upper atmosphere, only a single EUV observation of Mars and a handful for Venus have been reported (e.g., Krasnopolsky et al. 1994; Bertaux et al. 1981; Hord et al. 1991). As a result, EUV observations of terrestrial planets remain an almost unexplored domain. Even the first round of discovery missions will not fill this gap.

Terrestrial EUV observations started with broadband photometric measurements from sounding rockets and satellites which obtained the intensity distributions of the bright features from the geocorona (H I Lyman α and He I 584 Å), nighttime ionosphere (O I 911 Å, 1304 Å, and 1356 Å features), plasmasphere (He II 304 Å), and the interplanetary medium (He I 584 Å and He II 304 Å) [for an excellent review of Earth's EUV airglow see Meier (1991)]. Detailed experimental and modeling studies have shown evidence for the upflow of ionospheric ions in the magnetosphere (Chiu et al. 1986), detected the presence of a non-thermal population of atomic oxygen (Cotton et al. 1993), inferred solar line center flux and line width from He I 584 Å airglow (Bush & Chakrabarti 1995), and obtained the ionospheric temperature from the shape of O I recombination continuum (Feldman et al. 1992).

The atmospheres of Mars and Venus have been observed in the FUV from a number of U.S. and Soviet spacecraft. He I 584 Å emission from Venus was observed by the Ven-

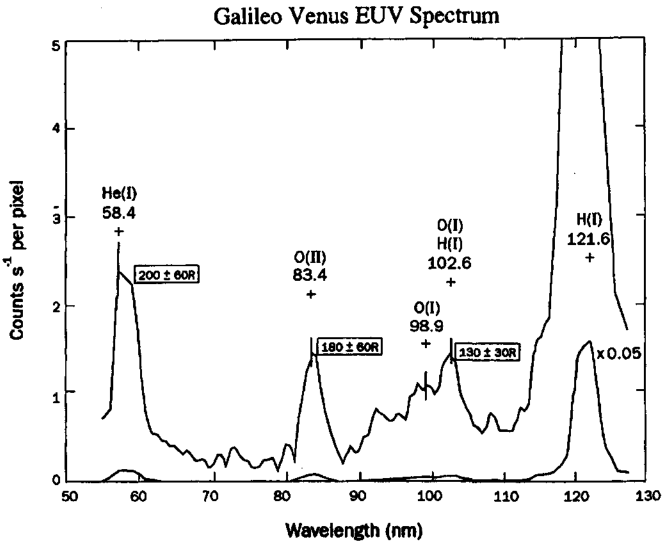

FIGURE 2. Venus airglow spectrum obtained by the Galileo UV spectrograph.

era 11/12 spacecrafts (Chassefiere et al. 1986). O II 834 Å emissions and, surprisingly, argon emissions at 869 Å and 1048 Å were also recorded by Venera missions. These observations were conducted by broadband instruments, however, which makes unambiguous determination of atmospheric composition a difficult task (Bertaux et al. 1981). In particular, the argon detections are especially suspect. On its trip to Jupiter, the Galileo spacecraft obtained an EUV spectrum of Venus (Hord et al. 1991), which includes several features due to O, O^+, He and H (Figure 2).

EUV spectroscopy of Mars and Venus can provide important clues for understanding not only the present structure of their upper atmospheres, but also their outgassing history. The first step towards that goal was achieved by the *EUVE* mission in January 1993, when it observed the He I 584 Å feature on Mars (Krasnopolsky et al. 1994). The observed spectrum shows the presence of martian helium emissions above the geocoronal background. The measured brightness of the He I 584 Å emission was 43 Rayleighs, which results in an inferred lifetime of 5×10^4 years for helium in the martian atmosphere.

A recent sounding rocket experiment by S. A. Stern and colleagues obtained an EUV spectrum of Venus, and the *HUT* experiment aboard the Astro-2 mission obtained EUV spectra of Venus and Mars. These results, although they have not yet appeared in the literature, will undoubtedly provide new insights and improve our understanding of the upper atmospheres of the terrestrial planets.

4. Jovian Planets

Of the Jovian planets, Jupiter remains the most extensively studied at EUV wavelengths. The UVS experiments on the Voyager 1 and 2 spacecraft have provided the primary EUV spectroscopic data set for the giant planets and their satellites. The EUV spectra of the Jupiter, Saturn, and Uranus, when properly scaled by their heliocentric distances, appear very similar (Yelle et al. 1987). They do differ, however, above 1100 Å, and the UVS data at these longer EUV wavelengths have been used to infer upper atmospheric composition.

The highest spectral resolution observations of Jupiter in the EUV were obtained by the *HUT* spectrograph aboard the Astro-1 (Feldman et al. 1993) and Astro-2 missions. These measurements clearly indicate the hydrogen Lyman series of lines as well as fluorescence emissions excited by solar Lyman β.

The *HUT* observations at superior spectral resolution have provided important new insight into the controversy over H_2 band airglow emissions seen on Jovian planets. Feldman et al. (1993) noted that an electron impact excitation source due to atmospheric dynamo, such as that proposed by Clarke et al. (1987), is required to explain the data. This source is needed in addition to solar fluorescence (Yelle et al. 1987), which accounts for up to 22%, and photoelectrons (Waite et al. 1983).

Recently, the *EUVE* mission observed the Jupiter and Io system in conjunction with the comet Shoemaker-Levy 9 impact. The data show an increase of Jupiter's He I 584 Å brightness by about a factor of 1.5 during the comet impact over its pre-impact value. Gladstone et al. (1995) surmise that the most likely explanation for the increase is the rising of helium in the impact-generated plumes from the well-mixed lower atmosphere into the depleted upper atmosphere. The extra helium in the upper atmosphere is then able to scatter more sunlight at 584 Å. An investigation of the EUV light curves obtained by *EUVE* shows the He I 584 Å enhancement during individual comet fragment impacts for the larger fragments (G, H, and K). The 1–2 hour delay of the brightening of the signal indicates the time required for substantial lateral expansion of the plumes as the impact sites rotate toward the direction of Earth.

Strong EUV emissions from the Io Plasma Torus (IPT) were discovered by the UVS instrument during the flyby of Voyager 1 (Broadfoot et al. 1979). The IPT is the only substantial emitter of EUV radiation (rather than simply being a reflector of sunlight) in the solar system. Sulfur and oxygen ions in a relatively dense plasma torus ($\sim 10^3$ cm^{-3}) surrounding the orbit of Io are excited by electron impact to radiate at several characteristic EUV wavelengths. Most of the energy for the torus comes from Jupiter's rotation. As neutral sulfur and oxygen atoms escape from Io through sputtering or other mechanisms, they are likely to become ionized and join the torus population. As they do so, they are swept up by Jupiter's corotating magnetic field which, since it moves much faster than Io's orbital velocity around Jupiter, gives the newly-formed torus sulfur and oxygen ions an energy boost of about 525 eV and 262 eV, respectively.

High-resolution EUV spectra of the IPT were obtained by the Astro-1 and Astro-2 missions. These spectra are totally dominated by emissions from the oxygen and sulfur ions (Moos et al. 1991). The *EUVE* spectrographs have also been used to study the IPT, and they have the advantage of being able to map out the spatial distribution of several of the EUV emissions over the entire torus (Hall et al. 1994). In addition to a strong dusk/dawn brightness asymmetry, the *EUVE* IPT data of the O II 539 Å feature also seem to indicate the presence of other torus-like features inside the orbit of Io (Figure 3). *EUVE* spectrometer data of the Io Plasma Torus before, during, and after the SL-9 impacts show no significant change in their relative brightnesses (Hall et al. 1995).

For the other outer planets, the Voyager UVS (Broadfoot et al. 1977) made extensive use of solar and stellar occultations to obtain atmospheric composition and temperature structure. This is possible due to the fact that the opacity of the atmosphere in different EUV wavelength regions can differ significantly (Broadfoot et al. 1989).

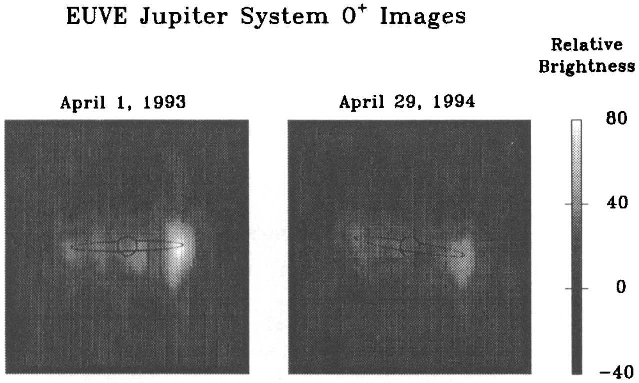

FIGURE 3. Images of the Jupiter (circle at the center) and Io Torus (dashed line) obtained at 539 Å by EUVE. Note the presence of torus-like features inside Io's orbit.

5. Satellites

While passing Neptune, the Voyager 2 UVS experiment obtained an EUV spectrum of Triton (Broadfoot et al. 1989), which showed that the primary features are due to various band systems of N_2. The other primary emission feature include the N II 1085 Å and H I 1216 Å lines. The authors noted that the data do not include positive detections of CO, Ar and Ne. From the absolute brightness and day/night asymmetry of the observed intensity of H I Lyman α, the authors concluded that photoelectrons and magnetospheric electrons might be responsible for some of the features.

The extended atmosphere of Triton, which resembles that of Pluto (and also somewhat that of Titan), also contributes to the formation of a proposed "plasma arc" (partial torus) around Neptune. Broadfoot et al. 1989 used this model to explain the presence of H I Lyman β emissions in the aurora and the relative absence of H I Lyman α.

6. Comets

A sounding rocket observation (Green et al. 1991) of Comet Austin in the 910–1180 Å band at approximately 3 Å resolution revealed an emission feature at 1128 Å which the authors attributed to a forbidden line of atomic oxygen. Such a feature has not been observed in the laboratory or in the terrestrial atmosphere, nor in any other comet spectrum (Feldman et al. 1991), and has raised an interesting controversy regarding atomic spectroscopy [see, for example, Slanger (1991) and its response]. Green et al. 1991 argue that the optically thick conditions that might explain the presence of 1128 Å emission might be present due to the large extent of the coma in a dynamically new comet.

The EUV data from this same sounding rocket flight were used to obtain limits on the relative abundances of cometary helium and argon (Stern et al. 1992). Although only upper limits to the abundances were possible, this was the first constraint of He and Ar abundances in comets. The authors found that the relative abundance of He/O in comet Austin is 1.5×10^4 depleted and no more than 30 times enriched in Ar/O compared to solar abundances. The He/O depletion can be used to infer that the cometary nuclear ices are not always maintained within a few degrees of absolute zero.

7. The Interplanetary Medium

There have been only limited observations of the interplanetary medium in the EUV. The Voyager UV spectrometer, with a 1.5×10^6 seconds exposure, has collected a spectrum of the sky in the direction of the North Galactic Pole (Holberg 1986). This observation, clearly contains the He I 584 Å feature produced by resonance scattering of solar emissions by neutral helium atoms in the heliosphere. The interpretation of this emission has subsequently raised the possibility that the solar 584 Å line is redshifted (Chassefiere et al. 1988).

The presence of 0.02 Rayleigh (1.6×10^3 photons cm^{-2} sec^{-1} ster^{-1}) of He II 304 Å emissions was observed in the photometric data obtained during the Apollo-Soyuz mission in the Earth's shadow cone (Paresce et al. 1981). These data were interpreted as due to multiple scattering of solar emissions, either by plasmaspheric He$^+$ ions or by He$^+$ in the interstellar medium produced by photoionization of He. A more recent analysis of *EUVE* survey observations obtained brightnesses of 1.30 Rayleigh, 0.040 Rayleigh, and 0.029 Rayleigh for the He I 584 Å, 537 Å, and the He II 304 Å emissions, during an exposure of 575,232 seconds looking down Earth's shadow (Jelinsky et al. 1995). As with the Apollo-Soyuz data, it is unclear what portion of these signals is due to multiple scattering in Earth's geocorona and plasmasphere.

On its way to Jupiter the Galileo spacecraft has made routine spectroscopic observations of the interplanetary medium (Hord et al. 1991). Although only the hydrogen Lyman α observations have been analyzed to date, He I 584 Å data also exist and are undergoing detailed analysis.

8. Summary

As EUV instruments have become more sensitive, with higher spectral and spatial resolution than the early exploratory ones, newer insights are being obtained regarding planetary atmospheres and their surfaces. Already several questions raised by the Voyager mission have been addressed by the Astro-1 and *EUVE* missions. The Astro-2 mission and several sounding rocket experiments have obtained new data on several solar system objects. Results from these data have not been reported yet. We also note that neither *EUVE* nor *HUT* is ideal for solar system studies, since *EUVE* was designed to either avoid detection or otherwise suppress many spectral features found in planetary atmospheres, and *HUT* lacked imaging capability. Progress in EUV instruments and availability of space flight opportunity will undoubtedly continue to increase our knowledge and understanding of the solar system.

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