Lunar albedo at hydrogen Lyman α by the NOZOMI/UVS

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The geometric albedo of the Moon at the wavelength of hydrogen Lyman α (HLyα 121.6 nm) was derived from an imaging observation by the ultraviolet imaging spectrometer (UVS) during the lunar encounter of the NOZOMI spacecraft. The solar HLyα irradiance data measured by the UARS/SOLSTICE at the time of UVS observation were adopted. We obtained an average geometric albedo of $5.2 \pm 0.9\%$ for the sunlit region where the UVS observed. Our result agrees with the geometric albedos obtained from the observations by Apollo 17 and Astro-2/HUT, though the observation geometry and area are completely different from each other. There exists a significant difference of the albedos from place to place in the observed lunar surface ranging from $2.3 \pm 1.1\%$ to $6.0 \pm 1.0\%$. It is noted that the observed contrast at the FUV wavelength is positive to that seen in the visible region.

1. Introduction

Reflectivity of a planetary disk is one of the most primitive parameters obtained by optical remote sensing from a distance. There are two definitions of planetary reflectance or albedos: the Bond albedo and geometric albedo. The former is defined by the ratio of the total amount of reflected light to the total amount of incident light. This value is important especially for planets with atmosphere in order to estimate total energy input. The latter is defined by the ratio of the actual intensity of light reflected by a planetary disk to that of a Lambertian surface or a perfect diffuser with the same size. The geometric albedo can be calculated not only for an entire planetary disk but also for a small part of a disk. The geometric albedo includes information on surface material and condition of planets without atmosphere.

The geometric albedo of the lunar surface in the FUV region was firstly reported by Lucke *et al.* (1976) using the data obtained by a scanning far-ultraviolet spectrometer onboard Apollo 17. From the observation data taken while the orbiter was in a lunar orbit for five days, geometric albedos of 4.4%–6.3% in the wavelength region of 122–168 nm were obtained. The second measurement was made by an ultraviolet spectrometer during fly-by of Mariner 10 (Wu and Broadfoot, 1977). The result shows rather small albedos compared with those obtained by Apollo 17. Another observation, though the spectral data did not include hydrogen Lyman α (HLyα 121.6 nm), was made by the Hopkins Ultraviolet Telescope onboard the Astro-2 Space Shuttle mission (hereafter Astro-2/HUT) obtaining the geometric albedos of 3.7% to 4.1% in the spectral region from 183 nm to 125 nm (Henry *et al.*, 1995). This result is more accurate than the past two observations and shows rather small spectral dependence of the lunar albedo.

The NOZOMI spacecraft is the first Japanese Mars orbiter launched on July 3, 1998. It spent about a half year in an orbit around the Earth before it was inserted into a Mars transfer orbit. During the Earth orbit it encountered with the Moon twice for swing-by. An ultraviolet imaging spectrometer (UVS) observed the lunar surface at the two lunar encounters. The geometric albedo of the Moon at the wavelength of HLyα was derived from the spectral data obtained at the first lunar encounter. Unfortunately, the distance between the spacecraft and the Moon during the observation period at the second encounter was too large to obtain useful data of the lunar surface.

2. Observation

Details of the UVS instrument onboard the NOZOMI spacecraft are described in Taguchi *et al.* (2000). The UVS-G consists of a collecting parabolic mirror, a slit, a concave grating, and photo-detectors and measures the spectral region of 110–310 nm with a spectral resolution of 2–3 nm. A spectrum in the FUV region is detected by an micro-channel plate with strip anodes. The UVS takes an image using spin and orbital motions of the spacecraft.

Observation of the lunar surface was made while the NOZOMI spacecraft approached the Moon on September 24, 1998. A lunar image at the wavelength of HLyα is shown in Plate 1. Figure 1 illustrates schematic geometry of the UVS observation. The distance between the center of the Moon and the spacecraft varied from 9,240 km at 05:44 UT to 6,800 km at 06:33 UT. The change in the distance causes distortion of the lunar outline depicted in the image. For comparison a visible image of the Moon taken by the Mars Imaging Camera (MIC) onboard the NOZOMI spacecraft (see `http://www.planet-b.isas.ac.jp/MIC/MIC-e.html`) is shown in Plate 2. This image is com-

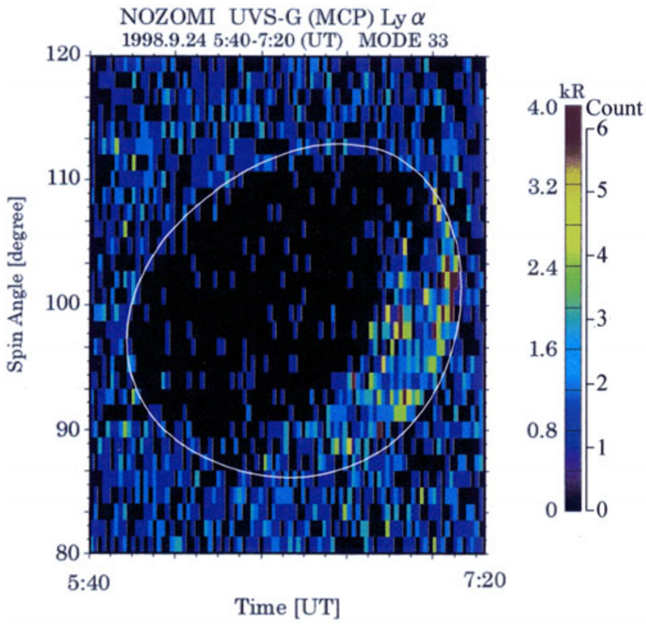

Plate 1. A HLyα image of the Moon taken by the UVS-G at the first encounter of the NOZOMI spacecraft to the Moon on September 24, 1998. The integration time for each pixel was 0.1 sec. A white oval shows the approximate outline of the Moon.

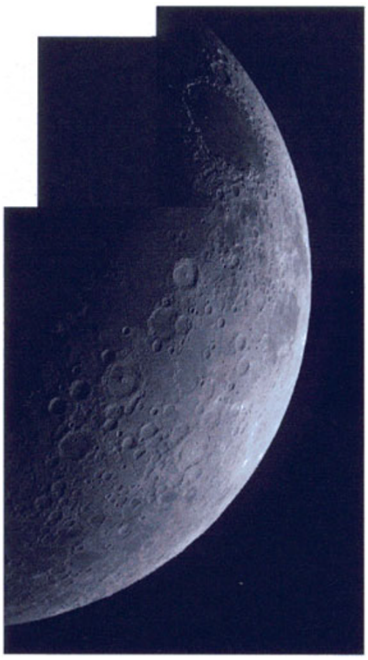

Plate 2. A composite image of the Moon taken by a visible camera (MIC) onboard NOZOMI on September 24, 1998. Sea of Crises is seen at the upper side.

position of several shots taken during the approach to the Moon.

Notation of the angles relevant to reflection of solar light at the lunar surface is also shown in Fig. 1. The angle between the direction of light incident into the lunar surface and the direction of observation α was almost constant around 130° during the observation period. The angle between the surface normal and the direction of incident light i varied from 52°

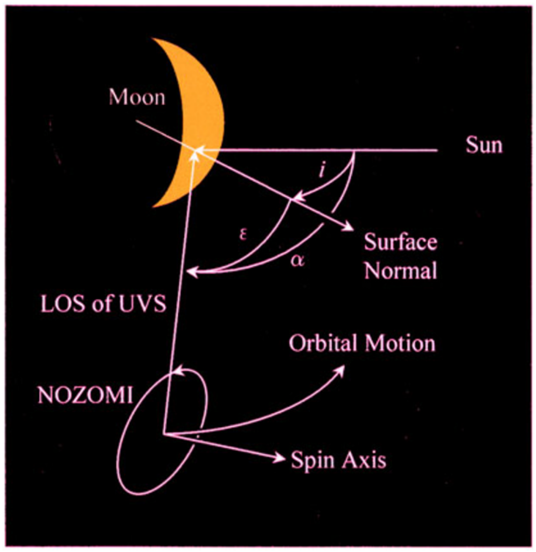

Fig. 1. Schematic of the observation geometry and notation of the angles relevant to the UVS observation of the lunar surface.

to 90°, while the angle between the surface normal and the direction of observation ϵ varied from 43° to 90°.

3. Data Analysis

The derivation of the geometric albedo is described in Hapke (1963). Here we follow Lucke *et al.* (1976) for notation of the equations. The observed intensity $I(i, \epsilon, \alpha)$ is expressed as

$$I(i, \epsilon, \alpha) = I_0 A\Omega b(\Sigma(\alpha)B(\alpha, g))/(1 + \cos\epsilon/\cos i), \quad (1)$$

where I_0 is intensity of incident radiation, $A\Omega$ instrumental throughput, b the total average reflectivity of the individual objects, $\Sigma(\alpha)$ average scattering law of the individual objects, and $B(\alpha, g)$ the retrodirective function. The assumptions on which Eq. (1) is derived are as follows (Hapke, 1963): 1) The surface consists of a semi-infinite layer of objects large compared with a wavelength of light and arranged in an open network into which light from any direction can penetrate freely. The objects are located irregularly enough within this structure so that on a macroscopic scale the medium appears isotropic and homogeneous. 2) The reflectivity of the individual objects is low. 3) The reflecting objects are oriented at random. 4) The intensity of light is exponentially attenuated in proportion to the path length of the ray through the medium. 5) All solid angles involved are small.

The functions $\Sigma(\alpha)$ and $B(\alpha, g)$ and a compaction parameter g in Lucke *et al.* (1976) are adopted. The values of i, ϵ, and α are calculated from the known positions of the Sun, the Moon and the spacecraft at the time of observation. Once we know the value of I_0 as described later, we can derive a value of b from Eq. (1) and the geometric albedo p according to Eq. (9) in Lucke *et al.* (1976):

$$p = \frac{\pi I(i, \epsilon, 0)}{I_0 A\Omega} = \frac{5b}{6}. \quad (2)$$

Surface luminosity data of the sunlit region where the field-of-view of UVS swept are used to derive an average geometric albedo. The data close to the limb, $\epsilon > 72^\circ$, are excluded, because a part of the field-of-view may have looked at the space. The data close to the terminator, where $i > 85^\circ$, are also excluded because of the shadowing problem. Geometric albedos are calculated using the spectral data only at HLyα, though the UVS covers the spectral region from 110 through 310 nm. The reasons why only this wavelength was chosen are that 1) the total counts of the UVS-G at HLyα are high enough compared with the other wavelengths and 2) the spectral response of the UVS-G was calibrated at three wavelengths including this wavelength (Taguchi *et al.*, 2000).

We have to know the solar HLyα irradiance I_0 at the time of observation to deduce the geometric albedo. Since the NOZOMI spacecraft has no instrument to monitor the solar ultraviolet irradiance, the UARS/SOLSTICE data are adopted. The SOLSTICE measures the solar ultraviolet irradiance in the wavelength range from 119 to 420 nm with spectral resolution of 0.1 to 0.3 nm, and the overall accuracy of absolute irradiance at the wavelength of HLyα is better than 10% (2σ) (Woods *et al.*, 1996). Daily mean solar spectral irradiance values are available from their WWW. At the time of UVS observation the sun was in the quiet period and no particular solar event was reported. Daily values of the solar irradiance on consecutive nine days including September 24, 1998 show very slight variation of $\pm 1\%$. Therefore, we consider that the daily mean value can be represented as the value at the time of UVS observation.

4. Result and Discussion

The result is shown in Table 1 together with the observations of lunar albedo at HLyα in the past. The error of $\pm 0.9\%$ in our result includes not only statistical error in the measurement but also spatial variability of the albedo. Unfortunately the most recent and precise measurement by the Astro-2/HUT experiment derives albedos only at wavelengths longer than 125 nm. However, the albedo in the wavelength range of 125–129 nm from Astro-2/HUT is added in Table 1 for comparison, because their results show very slight dependence on wavelength. The albedo derived from the Mariner 10 fly-by shows a significantly smaller value than the others. This value is also much smaller than the albedos at nearby wavelengths obtained from the same experiment (Wu and Broadfoot, 1977). Therefore, this measurement might contain an unknown error.

The Astro-2/HUT observations were conducted in nearly full-moon conditions, and, therefore, $\alpha = 0^\circ$ and $i = \epsilon$. In such a geometry the backscattered component is significant in the reflected light, and the observed albedo is an average over a hemisphere facing to the Earth. The spectrometer onboard Apollo 17 always looked at 30° from the local vertical ($\epsilon = 30^\circ$) but i varied from 5° to 75° and α from 10° to 100°. The observation by Apollo 17 was limited to the particular area in the low latitudes. The geometry and area of the NOZOMI/UVS observation differ from those of Apollo 17 and Astro-2/HUT. Nevertheless our result generally agrees with those of Apollo 17 and Astro-2/HUT.

It is noted that there exists a significant difference of the albedos from place to place ranging from $2.3 \pm 1.1\%$ to $6.0 \pm 1.0\%$. As expected by comparing the HLyα and visible images shown in Plates 1 and 2 the observed contrast at HLyα exhibits same tendency as seen in the visible light. Contrast of the FUV images taken by the UVS in the other wavelengths (an example is shown in Taguchi *et al.* (2000)), though they are not so good in quality as the HLyα image, also resembles that of the HLyα image. This evidence suggests that the contrast reversal on the lunar surface occurs shorter than the wavelength of HLyα. This is consistent with the observational result by Flynn *et al.* (1998), in which they found a high degree of reverse contrast at 20 nm, whereas the 60 nm image shows no detectable contrast.

Table 1. Measurements of lunar geometric albedos at HLyα and nearby wavelengths.

Experiment	λ (nm)	p
NOZOMI/UVS	121.6	$5.2 \pm 0.9\%$
APOLLO 17	121.6	6.3%
MARINER 10	121.6	2.1%
Astro-2/HUT	125–129	4.1%

5. Summary

The geometric albedo of the Moon at the wavelength of HLyα was derived to be $5.2 \pm 0.9\%$ for average of the sunlit region where the UVS observed. Our result is consistent with the geometric albedos obtained from the past observations by Apollo 17 and Astro-2/HUT. It is noted that there exists a spatial difference of the albedos ranging from $2.3 \pm 1.1\%$ to $6.0 \pm 1.0\%$, and the observed contrast is positive to that seen in the visible region.

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