Introduction: Lunar swirls are interesting albedo features on the Moon’s surface. In particular, Reiner Gamma swirl is the best object for understanding the polarimetric characteristics of lunar swirls because the swirl is located on the near side and a mare surface with outstanding observation conditions. Lunar space missions such as the Clementine, SELENE, SMART-1 and LRO performed photometry, but not polarimetry from lunar orbit. Therefore, polarimetric data of the Moon are available only for the nearside.

Polarimetry is a powerful tool for understanding the characteristics of the Moon’s surface because the light reflected by the surface of airless bodies is partially polarized, and the polarization states are dependent on the surface albedo, grain size, composition, and micro-structure. A polarimetric observation was performed by Lyot (1929) who found that the light scattered by the Moon’s surface was partially polarized [1]. After that, a correlation between the median grain size and the maximum polarization degree was revealed [2, 3]. Recently, Jeong and his colleagues performed high-resolution polarimetric observations at U, B, V, R and I passbands [4]. They found a latitude dependency of the particle size in the lunar regolith. However, the polarimetric behavior of lunar swirls is not well-known. Here, we extend the work of [4] and analyze the polarimetric behavior of Reiner Gamma swirl.

To understand the regolith characteristics of Reiner Gamma swirl, two polarimetric approaches were performed. First, we found that the swirl has a unique position on the I – Q space, where I and Q are two Stokes parameters, intensity and linear polarization. Second, we constructed a polarimetric phase ratio map for two polarization directions, those perpendicular (Γ⊥) and parallel (Γ∥) to the scattering plane, and we found the behavior of the polarimetric phase ratios of the lunar disk. This is the first attempt to make a polarimetric phase ratio for the lunar surface. The phase ratio Γ is constructed by an image of the ratio between the images taken at two different phase angles (Γ = Iα1 / Iα2, α1 > α2). The phase ratio technique is the simplest way to obtain the slope in the phase curve (reflectance as a function of phase angle).

The phase curve contains information on the topography, composition, albedo, and micro-structure of the reflecting surface on airless bodies such as the Moon [5, 6, 7]. The phase curve becomes steeper when the surface roughness increases because the area of the shadow becomes wider at the rougher surface when the phase angle is large. This is called a shadow-hiding effect [8]. The phase curve is also affected by the albedo. The higher the surface albedo, the brighter the shadow. This is because the brightness of the shadow is influenced by the intensity of multiply scattered photons, which is highly dependent on the single scattering albedo, and because the multiply scattered light is diffused more isotropically. Thus, I∥ makes the phase curve shallower. Consequently, the phase curve slope is inversely related to the albedo [9, 10]. The micro-structure of the surface is also known as one of the important factors for the phase curve of the Moon [8, 10, 11].

Figure 1 Distribution of the I versus Q. The dashed lines indicate the polarization degree at the given position. The contour lines are for the 50th, 75th and 95th.
Data: We employed the polarimetry data from Jeong et al. (2015). The spatial resolution of the data is about 1.34 km at the center of the lunar disk. We employed the B band data at phase angles 50° and 96°. We applied a disk function suggested by Shkuratov et al. (2011) to the intensity data to consider the effects of incidence and reflectance angles.

Results: Q, the linear polarization, was obtained by a subtraction of intensities ($Q = I_\perp - I_\parallel$). For the lunar surface, Q is dominantly sensitive to the roughness, grain size and albedo [3]. Therefore, Q gives information on the characteristics of the regolith, which are the key factors in understanding the characteristics of swirfs.

We found a new polarimetric peculiarity for Reiner Gamma swirl. Figure 1 shows the polarimetric behavior of the swirl at phase angles 50° (upper) and 96° (bottom). The contour lines mark the mare and highland regions, where the maria are marked in blue and the highlands are marked in red. The contour lines are for the 50th, 75th and 95th percentiles. The filled circles indicate Reiner Gamma swirl.

The Q value of the swirl is significantly different from those of the maria. However, the I value of the swirl is similar to the highlands. Thus, the swirl has a lower polarization degree P than the background mare surface. The smaller P of the swirl could be explained in two ways. First, small grain sizes make I greater because the absorption coefficient decreases with the volume of the particle. Thus, the small P values agree with the median grain size measurements of Reiner Gamma swirl [4]. Second, if the micro-structure (“fairy castle”) in the regolith of the Reiner Gamma swirl has been destroyed, the polarimetric variation could be explained. I increases 3~12% when the micro-structure has been destroyed [7, 11, 10]. For example, landing sites exhibit the same effect. All of the lunar landing sites are brighter than their neighbors. The micro-structures of the landing sites were certainly destroyed by the rocket exhaust when the landers were approaching the lunar surface [7, 10, 11, 13]. We analyzed the polarimetric phase ratio to understand the micro-structure states of the swirl Reiner Gamma.

The slope of the phase curve is affected by micro-structure. In particular, $\Gamma_1$ is more sensitive to the micro-structure than $\Gamma_2$ because $I_1$ is not affected by the shadow-hiding effect.

Figure 2 shows global trends of $\Gamma_1$, $\Gamma_2$, and $\Gamma_1$ versus the albedo. Reiner Gamma swirl is marked as red circles. The inverse correlation between $\Gamma_1$ and the albedo is clearly seen. High albedo regions are shown as smaller $\Gamma_1$ values because the brightness of the shadow is determined by the multiple scattering intensities, which are induced by the single scattering albedo [9, 10]. Thus, the inverse correlation between the albedo and the phase curve slope is manifested globally.

In Fig 2c, the swirl has a smaller $\Gamma_1$ value than the average. This implies that the phase curve of the swirl was influenced by the micro-structure variation apart from the albedo effect. It is a result that is consistent with the photometric phase ratio $\Gamma$ of the Reiner Gamma swirl [10, 14]. We suggest that the regolith micro-structure of Reiner Gamma swirl has been destroyed or the swirl has a larger fine grain fraction due to destroyed micro-structure.

Conclusions: We analyzed the polarimetric characteristics of the Reiner Gamma swirl. We found a new polarimetric peculiarity of Reiner Gamma swirl: the swirl has Q values as high as the maria but P is smaller than the maria. Additionally, we found the polarimetric phase ratio $\Gamma_1$ of the swirl is smaller than the average. We suggest that the polarimetric characteristics of the swirl are caused by destroyed regolith micro-structure or a combination of the destroyed micro-structure and a relatively large fraction of fine grains.