EXPERIMENTAL SCATTERING MATRIX FOR LUNAR REGOLITH SIMULANT JSC-1A AT VISIBLE WAVELENGTHS.

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ABSTRACT

We present the experimental scattering matrix as a function of the scattering angle of the lunar soil simulant JSC-1A. The measurements were performed at 488 nm, 520 nm and 647 nm, covering the range of scattering angles from 3° to 177°. The effect of sub-micron size particles on the measured phase function and degree of linear polarization has been studied. After removing particles smaller than 1 μm radius the forward scattering peak becomes steeper. Further, the maximum of the degree of linear polarization increases, moving toward smaller scattering angles. Interestingly, the negative branch at backward direction disappears as the small particles are removed from the sample. As multiple scattering calculations with polarization included require single scattering matrices in the whole scattering range (from 0° to 180°), we computed the corresponding synthetic scattering matrix through an extrapolation method, considering theoretical boundary conditions. From the extrapolated results, the asymmetry parameter g and the back-scattering linear depolarization factor δ_L were computed.

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1. INTRODUCTION.

First polarimetric studies date back to [Lyot \(1929\)](#). More recently, there has been an increasing interest in polarimetric measurements since the work of [Sterzik et al. \(2012\)](#) who presented a new method to detect spectropolarimetric biosignatures in earth-like exoplanets. In order to improve the accuracy of this method, the background signal produced by lunar regolith has to be characterized with precision to subtract it from the spectrum.

Apollo missions brought to Earth 382 kilograms of lunar samples between 1969 and 1972. In addition, some 300 grams of sample were returned from the Moon by Luna's automated missions. Due to the limited amount of lunar samples available to study, lunar simulants were developed to cover that need. In the early 1990s, a mare lunar regolith simulant called JSC-1 (Johnson Space Center-1, [McKay et al.](#)) was produced to support NASA's future lunar surface missions. This simulant was created to resemble as much as possible the composition and size distribution of lunar soil 14163 from the Apollo 14 mission. When this simulant ran out, NASA ordered a new simulant called JSC-1A, matching the JSC-1 simulant as closely as possible. This simulant has been studied from various points of view, but to our knowledge, its scattering matrix has never been measured.

In this work, we present the experimental scattering matrices as functions of the scattering angle of the JSC-1A lunar simulant at three visible wavelengths (488 nm, 520 nm, and 647 nm). These measurements were performed at the IAA COsmic DUst LABoratory (CODULAB) located at the Instituto de Astrofísica de Andalucía (IAA) ([Muñoz et al. 2010](#)). The experimental apparatus is presented in Section 2. The description of the physical properties of the JSC-1A samples is presented in Section 3. The lack of measurements at very small and very large scattering angles (0-3° and 177°-180°) limits the applicability of the measured scattering matrices for multiple scattering calculations. Therefore, we extrapolate the experimental scattering matrices to cover the entire 0°-180° angle range. The extrapolation of

the components of the scattering matrix F was performed following the procedure presented by [Liu et al. \(2003\)](#) for the phase function and [Muñoz et al. \(2006\)](#) for the rest of scattering elements. The asymmetry parameter g and the back-scattering linear depolarization factor $\delta_L(180^\circ)$ were calculated from these extrapolated matrices. All these results are presented in Section 4. Conclusions are drawn in Section 5.

2. EXPERIMENTAL APPARATUS.

In this section, we give a brief description of the IAA-CODULAB apparatus. A detailed description, including the calibration process and data acquisition, is presented in [Muñoz et al. \(2010\)](#). All published results are freely available at the Amsterdam-Granada light scattering database (<http://www.iaa.es/scattering>).

We use an Argon-Krypton laser that is tunable to five different wavelengths in the visible range. In this work, we present the results at 488 nm, 520 nm, and 647 nm. The laser beam passes through an integrated polarizer and an electro-optic modulator, which in combination with lock-in amplifiers and an oscillator allows us to increase the accuracy of the measurements as well as determine several elements of the scattering matrix simultaneously. The laser beam is scattered by a cloud of particles produced by an aerosol generator. Two photomultipliers located in a one meter ring collect the signal. One of them, the monitor, is located in a fixed position to correct for fluctuations of the jet stream, while the other acts as a detector, moving from 3° to 177° . Two additional optical elements, a quarter-wave plate and an analyzer, are optionally placed in the detector photomultiplier. By using five different configurations of these optical elements, we measure the 4×4 scattering matrix, which has only six independent elements when assuming mirror symmetry and randomly oriented particles in the sample (see Eq. 1),

$$\mathbf{F} = \begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix}. \quad (1)$$

The scattering matrix elements depend on the wavelength λ and on the particle size, shape distribution, and complex refractive index of the particles. The elements also depend on the scattering angle θ , which is the angle defined by the directions of the incident and scattered beams. All scattering elements $F_{ij}(\theta)$ are normalized to $F_{11}(\theta)$, except $F_{11}(\theta)$ itself, which is normalized to unity at 30° . The $F_{11}(\theta)$ element normalized in this way is called the phase function in this work. The $-F_{12}(\theta)/F_{11}(\theta)$ ratio is equivalent to the degree of linear polarization for unpolarized incident light.

From the $F_{22}(\theta)/F_{11}(\theta)$ ratio, we can compute the linear depolarization factor at back-scattering δ_L according to the equation ([Mishchenko et al. 2002](#)):

$$\delta_L = \frac{F_{11}(180^\circ) - F_{22}(180^\circ)}{F_{11}(180^\circ) + F_{22}(180^\circ)}. \quad (2)$$

The validity of the measurements has been tested by comparing spherical water droplet measurements with Lorenz-Mie computations for homogeneous spherical particles ([Muñoz et al. 2010](#)). Moreover, special tests have been carried out to test that our measurements are performed under single scattering conditions ([Muñoz et al. 2011](#)). Further, we checked that the measured scattering matrices fulfilled the Cloude coherence matrix test within the experimental errors at all measured scattering angles ([Hovenier et al. \(1986\)](#)).

3. PHYSICAL PROPERTIES OF JSC-1A LUNAR SIMULANT.

As mentioned, the JSC-1A mare regolith simulant was produced to match the Apollo 14 sample 14163. In Table 1, we present a composition comparison between simulant JSC-1A and the Apollo 14 sample 14163. The JSC-1A material was mined from a commercial cinder quarry at Merriam Crater ($35^\circ 20' \text{ N}$, $111^\circ 17' \text{ W}$), a volcanic cinder cone located in the San Francisco volcano field near Flagstaff, Arizona. No chemical processing was performed on the simulant.

3.1. Size characterization.

The original mined material from the cinder quarry was milled and sieved to approximate the finer component of lunar regolith, where an important percentage of grain sizes are below $20 \mu\text{m}$. Before using the JSC-1A in our light scattering experiment, we removed the large grains by using a sieve with $140 \mu\text{m}$ grid width to avoid clogging the

Constituent oxides	Apollo 14 sample 14163 (Papike et al. 1982)	JSC-1A (Ray et al. 2010)
SiO ₂	47.3 %	45.7 %
Al ₂ O ₃	17.8 %	16.2 %
CaO	11.4 %	10.0 %
FeO	10.5 %	-
MgO	9.6 %	8.7 %
TiO ₂	1.6 %	1.9 %
Na ₂ O	0.70 %	3.2 %
K ₂ O	0.55 %	0.8 %
MnO	0.135 %	0.2 %

TABLE 1. Composition in mass percentage (mass %) of the major constituents of the JSC-1A lunar simulant compared with the Apollo 14 sample 14163.

aerosol generator. The size distribution was then measured with a commercial particle sizer. This instrument measures the phase function of the sample at a wavelength of 632.8 nm at certain scattering angles, with special attention to the forward scattering peak. The angular patterns obtained of the phase function are compared to those simulated by the instrument software in order to retrieve the volume distribution that best fits the data. These simulations use either Lorenz-Mie or Fraunhofer theory. The data generated by these two methods are simplifications making the assumption of spherical particles to obtain numerical results. The Fraunhofer approximation does not require the refractive index as input to compute the volume distribution, but puts restrictions on the size of the particles since it is only applicable to particles larger than the wavelength of the incident light. In the Lorenz-Mie model we have used $m = 1.65 + i0.003$ as complex refractive index (Goguen et al. 2010). From the measured volume distribution, we compute the number distribution of the sample $n(r)$ such that $n(r)dr$ is the relative number of spheres per unit volume in the size range r and $r + dr$. The values of the effective radius r_{eff} and effective variance v_{eff} are computed accordingly to the equations Hansen and Travis (1974):

$$r_{\text{eff}} = \frac{\int_0^{\infty} r^3 n(r) dr}{\int_0^{\infty} r^2 n(r) dr}, \quad (3)$$

$$v_{\text{eff}} = \frac{\int_0^{\infty} (r - r_{\text{eff}})^2 n(r) dr}{\int_0^{\infty} r^2 n(r) dr}. \quad (4)$$

In Table 2 we present the resulting values for our JSC-1A sample.

As mentioned, during the experiment the cloud of particles is located in a jet stream produced by an aerosol generator. In this way we do not need a vessel to contain the sample. This is very convenient since the container would produce reflections or stray light decreasing the accuracy of the measurements and limiting the angular range. A disadvantage of this method is that we need a continuous flow of particles during the measurements, requiring a sufficient amount of sample. The sample has to be collected by a jet pump after being blown through the scattering volume. In an attempt to reduce this problem, we have used a dedicated pump for the JSC-1A sample to re-use it in case it might be needed for future measurements. To check how this recycling process changes the size distribution of the sample we have performed the following test: 17 g of the bulk JSC-1A sample has been recycled twice. After one recovery cycle, the mass loss was 1.6 g, 9.4 % of the original mass. After the second recovery, the loss was significantly smaller, being 0.4 g, 2.6 % of the 15.4 g of the first recovered material. The size distribution of the recycled sample was measured after the first and second recoveries. The r_{eff} of the sample after the first recovery changed from 15.85 μm to 20.62 μm , an increase of 30 %. After the second recovery, the r_{eff} value was 21.86 μm , an increase of 6 % from 20.62 μm . Therefore, during the recovery process a high percentage of the small particles fraction is lost. This losing effect tends to saturate after the first recovery. With regard to the v_{eff} , this value varies from 1.28 for the pristine sample, to 1.06 for the sample recovered once and 1.05 for the sample recovered twice. The size distribution becomes narrower, but again this effect saturates. In Figure 1 and Table 2, we show a comparison between the number size distributions

FIGURE 1. Number distribution $N(\log r)$ versus $\log r$ of the pristine lunar simulant JSC-1A (circles), same samples after recover it once from the collecting system (triangles) and after two recoveries (squares). Retrievals based on Mie and Fraunhofer theories are presented in the left and right panels, respectively. The refractive index used in the Mie light scattering model is $m = 1.65 + i0.003$.

as function of $\log r$, $N(\log r)$, where $N(\log r)d\log r$ can be defined as the relative number of spheres per unit volume in the size range $\log r$ and $\log r + d\log r$. We present also in Figure 2 $S(\log r)$, which can be defined as the relative contribution to the total surface area of projected-surface-area-equivalent spheres of radius r as function of $\log r$. As the area under the curve is normalized to unity, we observe that the recovered sample has lost the contribution of the small particles to the size distribution.

Sample	Mie		Fraunhofer	
	$r_{eff} (\mu m)$	v_{eff}	$r_{eff} (\mu m)$	v_{eff}
Pristine	15.85	1.28	10.50	1.69
Recovered once	20.63	1.06	13.80	1.42
Recovered twice	21.86	1.05	14.67	1.45

TABLE 2. Size distribution parameters r_{eff} and v_{eff} for the pristine sample, the sample after recover it once, and twice. Retrievals based on Mie and Fraunhofer theories are presented in the left and right panels, respectively. For the Mie model, the refractive index used was $m = 1.65 + i0.003$ (Goguen et al. 2010).

3.2. Shape characterization.

A deep analysis of the JSC-1A particle shape is presented in Garboczi (2011), where X-ray computed tomography (X-ray CT) was used to characterize the simulant. In this work, we use same techniques to describe our sample.

In Figure 3, we show X-ray CT images qualitatively showing the shape variation in the JSC-1A lunar simulant. To prepare samples, the particles of interest were mixed with epoxy and the mixture pulled into a narrow (3 mm diameter) plastic tube. Pieces of the tube were cut and used in the upright position as samples in one of two X-ray microCT instruments. For the image in Figure 3c, the epoxy-particle mixture was dripped on the outside of the same tube, to give a thinner sample. The thinner sample gave better images at this very high resolution than the regular samples.

Figure 3a is approximately 1.04 mm in width. Notice the air bubbles in some of the particles. Since JSC-1A has a volcanic origin, these must be the remnants of air bubbles that were entrained during the original lava flow. The large particle in the right of the image seems to be a conglomerate of large and small particles.

Figure 3b is approximately 1.12 mm in width. Note that Figure 3b is about the same physical size as Figure 3a, but the large particles have been eliminated by sieving through a 75 μm sieve and many of the smaller particles have been eliminated by sieving through a 20 μm sieve. Note the irregular, non-spherical shapes, typical of a ground rocky material.

Figure 3c is approximately 0.16 mm in width. As in the previous panel, the material used to make these images

FIGURE 2 . Projected-surface-area distribution $S(\log r)$ versus size logarithm $\log r$ of the pristine lunar simulant JSC-1A (circles) and same sample after recover it once from the collecting system (triangles). The Mie light scattering model has been used to compute the size distribution with a refractive index of $m = 1.65 + i0.003$ (Goguen et al. 2010). The cut slope seen for small sizes is an artifact produced by the retrieved data from the commercial particle sizer.

passed the 75 μm sieve and were retained on the 20 μm sieve. Again note the irregular, non-spherical shapes, typical of a ground rocky material. The particle at the left bottom corner (inside circle) is about 16 μm in width, in this cross-section.

In Figure 4, we show four scanning electron microscope (SEM) images of the JSC-1A sample. Figures 4a and 4c correspond to the pristine sample, while Figures 4b and 4d correspond to the recovered sample from the pump.

The angularity of the shape is a common feature at all sizes. As can be seen, the irregularity is the norm. In general, the particles also seem somewhat glassy and faceted, as might be expected from ground volcanic material. Another sign of the volcanic origin of the sample can be perceived in the three central particles in Figure 4c, where traces of enclosed gas bubbles can be seen in the surface of those particles. In Figure 4f, some very small particles clinging to the larger particle surfaces. It is probable that these small particles are only clinging through electrostatic forces. The particles show a very soft and almost featureless surfaces. In Figure 4b, we show some particles about 15 μm in radius, which is the characteristic size of this sample as presented above. Qualitatively, based on these admittedly small amount of particles, we can affirm that particle shape is roughly invariant with respect to particle size. This has been seen before for crushed natural particles (Garboczi et al. 2012), albeit at a somewhat larger size scale. Figures 4c and 4d have a similar magnification, so here we can observe the difference between the pristine and the recovered sample. In Figure 4c the very small particles seem to be more abundant than in Figure 4d, which is consistent with the size distribution r_{eff} values presented in Table 2.

4. EXPERIMENTAL SCATTERING MATRIX.

In Figure 5, we present the experimental scattering matrix elements as functions of the scattering angle at three different wavelengths (488 nm, 520 nm, and 647 nm). The measurements cover the scattering angle range from 3 to 177°. The ratios $F_{13}(\theta)/F_{11}(\theta)$, $F_{14}(\theta)/F_{11}(\theta)$, $F_{23}(\theta)/F_{11}(\theta)$ and $F_{24}(\theta)/F_{11}(\theta)$ are not represented since they were found to be zero over the entire angle range within the accuracy of the measurements (as expected by Eq. 1). The experimental errors are represented as error bars (note that some error bars are smaller than the symbol itself). The main source of noise is the statistical variation of the number of large particles passing through the scattering volume, resulting in a smaller signal-to-noise ratio.

The $F_{11}(\theta)/F_{11}(30^\circ)$ ratio, which we have previously defined as the phase function, shows the usual behaviour of large irregular mineral dust, i.e. a strong forward peak and almost no structure at side- and back-scattering, as shown in Fig. 5a. The forward diffraction peak can be used to characterize the mean size of the particles as it increases as the particle size grows (Liu et al. 2003). We do not observe any significant difference in the measured values of $F_{11}(\theta)/F_{11}(30^\circ)$ with the wavelength. As stated above, the scattering elements depends mainly on size, shape and refractive index of the sample. The lack of differences between wavelengths is indicative of a flat dependence of the imaginary part of the refractive index with the wavelength. Also the relative size to the wavelength does not significantly changes at the measured wavelengths. We have to take into account that some minor differences in the

FIGURE 3 . X-ray CT images of the JSC-1A sample. The particles were mixed with epoxy and introduced in a 3 mm diameter tube before cutting into slices. Panel (a) depicts the bulk sample, as no sieving was performed. Panel (b) shows particles in the size range of 20 μm to 75 μm after removing larger and smaller particles through sieving. Panel (c) shows the same population as (b), but with larger magnification.

phase function may appear between wavelengths, but the logarithmic representation and the arbitrary normalization to unity at 30 degrees may fade them out.

The $-F_{12}(\theta)/F_{11}(\theta)$ ratio, shown in Fig. 5b, equals the degree of linear polarization for unpolarized incident light. This plot presents the typical bell shape, with a maximum of polarization near 90° and a small inversion branch at back-scattering (~ 2 % of negative polarization). The maximum of the degree of linear polarization shows slightly larger values at 647 nm than at 488 nm, i.e. it presents a red polarization color. This has been observed consistently in our database in silicate-type particles when the imaginary part of the refractive index has a constant dependence on the wavelength (see e.g. Muñoz et al. 2012; Dabrowska et al. 2015).

FIGURE 4. Scanning electron microscope images of the JSC-1A pristine sample and recovered from the jet pump. Panels (a) and (c) correspond to the pristine sample, and panels (b) and (d) correspond to the recovered sample.

The $F_{22}(\theta)/F_{11}(\theta)$ ratio, shown in Fig. 5c, is commonly used as a proof of the non-sphericity of the particles, since this ratio equals unity at all scattering angles for optically inactive spheres. The JSC-1A sample shows a $F_{22}(\theta)/F_{11}(\theta)$ ratio different from unity at nearly all measured scattering angles. The depolarization factor (Eq. 2) also depends on this ratio. No significant differences are found between the studied wavelengths.

The $F_{33}(\theta)/F_{11}(\theta)$ and $F_{44}(\theta)/F_{11}(\theta)$ ratios, shown in Fig. 5d and 5f respectively, can be studied jointly also as a sign of non-sphericity, indicating irregular particles when they are different from each other (Mishchenko et al. 2000). The measured $F_{44}(\theta)/F_{11}(\theta)$ ratio for the JSC-1A sample is larger than the $F_{33}(\theta)/F_{11}(\theta)$ ratio in the $\sim 75^\circ - 177^\circ$ scattering angle range, while in the case of homogeneous spherical particles the $F_{33}(\theta)/F_{11}(\theta)$ ratio is equal to the $F_{44}(\theta)/F_{11}(\theta)$ ratio at all scattering angles.

The $F_{34}(\theta)/F_{11}(\theta)$ ratio, shown in Fig. 5e, shows the strongest wavelength dependence of all measured scattering matrix elements.

Further, we have studied the effect of the loss of small particles on the scattering matrix elements. Due to limited amount of recycled sample we have only measured the $F_{11}(\theta)$, $-F_{12}(\theta)/F_{11}(\theta)$ and $F_{22}(\theta)/F_{11}(\theta)$ ratios at 520 nm. In Figure 6, we present the latter scattering elements for the pristine sample and the JSC-1A simulant after one recovery. As stated above, the smaller particles of the sample are depleted during the collecting process. The effect of this depletion on the scattering matrix is noticeable. In the phase function in Fig. 6a, we observe an increase of the forward scattering peak. This is expected as this diffraction peak depends on the particle size, being steeper for larger particles. The maximum of the degree of linear polarization increases by a factor of 1.5. Moreover, the maximum is moved toward smaller scattering angles. Apparently the small particles fraction were determining the maximum of the degree of linear polarization. This is consistent with simulations presented in Liu et al. (2015) for Gaussian random

FIGURE 5. Experimental scattering matrix for lunar simulant JSC-1A at three different wavelengths (488 nm, 520 nm and 647 nm).

FIGURE 6. The $F_{11}(\theta)/F_{11}(30^\circ)$, $-F_{12}(\theta)/F_{11}(\theta)$ and $F_{22}(\theta)/F_{11}(\theta)$ experimental scattering ratios for lunar simulant JSC-1A after recovery it once from the pump. The measurements were performed at 520 nm.

shapes. In those simulations, as the mean size parameter of the particles grows, we move from the resonance scattering region into the geometric optics regime, where the maximum in the ratio $-F_{12}(\theta)/F_{11}(\theta)$ increases as the size of the particles increases. The small particles are restricting the maximum of the degree of linear polarization. Another interesting feature observed in our results is that the negative polarization branch nearly disappears on the recovered sample. The $F_{22}(\theta)/F_{11}(\theta)$ ratio, shown in Fig. 6c, varies slightly at small scattering angles, but is unaffected at

back-scattering, so the depolarization ratio is not altered by the particle recovery process.

4.1. Synthetic scattering matrix.

As mentioned in Section 2, the laboratory measurements do not cover the whole scattering angle range from 0° to 180° . The lack of measurements at forward and back-scattering angles limits the use of the measured scattering matrix data for radiative transfer calculations. To facilitate the use of our experimental data we compute the so-called synthetic scattering matrix $\mathbf{F}^{\text{au}}$ from our measurements. This matrix is defined in the full scattering angle range. Therefore, what we measure in the laboratory is the relative phase function $F_{11}(\theta)/F_{11}(30^\circ)$, where (see Volten et al. (2006)):

$$\frac{F_{11}(\theta)}{F_{11}(30^\circ)} = \frac{F_{11}^{\text{au}}(\theta)}{F_{11}^{\text{au}}(30^\circ)}, \quad (5)$$

and $F_{11}^{\text{au}}(\theta)$ is the auxiliary phase function, which is normalized according to Eq. 6:

$$\frac{1}{2} \int_0^\pi \sin \theta F_{11}^{\text{au}}(\theta) d\theta = 1. \quad (6)$$

The auxiliary phase function $F_{11}^{\text{au}}(\theta)$ covers all the scattering angles from 0° to 180° . The extrapolation of the $F_{11}^{\text{au}}(\theta)$ element is computed as follows:

- The forward diffraction peak (0° – 3°) is computed based on the assumption that the forward diffraction peak for randomly oriented particles with moderate aspect ratios mainly depends on the size of the particles and is only weakly dependent of their shape (Liu et al. 2003). We use the Lorenz-Mie theory to compute the scattering produced by projected-surface-area equivalent spheres between 0° and 3° . These computations depends on the size distribution and the refractive index of the sample. For the refractive index, we use $m = 1.65 + i0.003$ (Goguen et al. 2010), while the size distributions are those presented in Section 3 (Table 2).
- Back-scattering extrapolation at 180° is performed using the least squares method for a quadratic function using the measured data from 150° to 177° . As the scattering of random oriented irregular particles must be symmetric with respect to the forward and backward directions, the first derivative for all the scattering elements must be null at 0° and 180° (Hovenier and Guirado 2014). The back-scattering is reproduced with a cubic spline interpolation between the last measured data point (177°) and the extrapolated $F_{11}^{\text{au}}(180^\circ)$ value, taking into account the null derivative condition.
- At this point, we have a data function given by the measured data from 3° to 177° and extrapolated data from 177° to 180° . This function is moved vertically until the value of $F_{11}^{\text{au}}(3^\circ)$, as computed by Lorenz-Mie theory, matches the measured value of $F_{11}(3^\circ)$.

The normalization condition given by Eq. 6 is then checked. If it is not satisfied within a 0.1 % accuracy, the value of $F_{11}(3^\circ)$ is increased or decreased (within the experimental error bars) depending on whether the integral is greater than, or smaller than unity, and the three step process is repeated.

The other missing values of the $\mathbf{F}^{\text{au}}$ matrix elements are interpolated considering the well-known set of constraints of scattering matrices at forward and backward scattering (Hovenier et al. 2004):

$$\frac{F_{12}^{\text{au}}(0)}{F_{11}^{\text{au}}(0)} = \frac{F_{12}^{\text{au}}(180^\circ)}{F_{11}^{\text{au}}(180^\circ)} = \frac{F_{34}^{\text{au}}(0)}{F_{11}^{\text{au}}(0)} = \frac{F_{34}^{\text{au}}(180^\circ)}{F_{11}^{\text{au}}(180^\circ)} = 0, \quad (7)$$

$$\frac{F_{22}^{\text{au}}(0)}{F_{11}^{\text{au}}(0)} = \frac{F_{33}^{\text{au}}(0)}{F_{11}^{\text{au}}(0)} = 1, \quad (8)$$

$$\frac{F_{22}^{\text{au}}(180^\circ)}{F_{11}^{\text{au}}(180^\circ)} = - \frac{F_{33}^{\text{au}}(180^\circ)}{F_{11}^{\text{au}}(180^\circ)}, \quad (9)$$

$$\frac{F_{44}^{\text{au}}(180^\circ)}{F_{11}^{\text{au}}(180^\circ)} = 1 - 2 \frac{F_{22}^{\text{au}}(180^\circ)}{F_{11}^{\text{au}}(180^\circ)}. \quad (10)$$

Only the value of $F_{22}^{\text{au}}(180^\circ)/F_{11}^{\text{au}}(180^\circ)$ must be extrapolated, using the same method of the $F_{11}^{\text{au}}(180^\circ)$ value explained above. In Figure 7, we present the results of this extrapolation for $\lambda=488$ nm. Note that measured $F_{11}(\theta)$

FIGURE 7. Comparison between the experimental scattering matrix of the JSC-1A lunar simulant at 488 nm (circles) and the extrapolated matrix (triangles). Note that measured $F_{11}(\theta)$ is normalized to unity at 30° whereas extrapolated $F_{11}^{au}(\theta)$ is normalized so that its average over all directions equals unity.

is normalized to unity at 30° whereas extrapolated $F_{11}^{au}(\theta)$ is normalized so that its average over all directions equals unity as stated in Eq. 6. Also, the $F_{34}(\theta)/F_{11}(\theta)$ ratio should tend to zero at back-scattering, but there is a gap between the last measured scattering angle and the back-scattering direction. This small disagreement could be due to a slight disadjustment in the V_{DC} during the measurement. Also, we see a step in the $F_{44}(\theta)/F_{11}(\theta)$ ratio. This is probably an artifact of the extrapolation, as this ratio depends on other scattering elements according to Eq. 10, so the error inherent to the extrapolations of $F_{11}(180^\circ)$ and $F_{22}(180^\circ)/F_{11}(180^\circ)$ is affecting this result.

The asymmetry parameter g is calculated from the extrapolated phase function using:

$$g = \frac{\int_0^\pi d\theta \sin \theta \cos \theta P_{11}^{au}(\theta)}{\int_0^\pi d\theta \sin \theta P_{11}^{au}(\theta)}. \quad (11)$$

The values of g are presented in Table 3. They are classified depending on the size distribution model used in the extrapolation of $F_{11}^{au}(\theta)$ (Mie or Fraunhofer) and for the three visible wavelengths used.

In Table 4, we present the computed depolarization factor $\bar{d}(180^\circ)$ using Eq. 2. The results are classified according to the wavelength and the light scattering model used in the extrapolation.

5. CONCLUSIONS.

We presented the 4×4 experimental scattering matrices for the lunar simulant JSC-1A at three visible wavelengths (488 nm, 520 nm, and 647 nm). The data were extrapolated at forward and back-scattering to obtain the synthetic matrices that cover the whole scattering range from 0° to 180° . The size distribution of the sample was also measured for the pristine sample and after being recovered twice from the collecting device to study the size-selection effect. Tables of the measured and synthetic scattering matrices are available in the Amsterdam–Granada Light Scattering

Asymmetry parameter g		
Wavelength λ	Mie	Fraunhofer
488 nm	0.74	0.57
520 nm	0.75	0.60
647 nm	0.74	0.59

TABLE 3. Asymmetry parameter g for the JSC-1A lunar simulant retrieved from the extrapolated phase function $F_{11}^{au}(\theta)$. The results are presented according to the light scattering model used in the extrapolation (Mie or Fraunhofer) and depending on the wavelength (488 nm, 520 nm and 647 nm).

Back-scattering depolarization factor $\delta_L(180^\circ)$		
Wavelength λ	Mie	Fraunhofer
488 nm	0.35	0.35
520 nm	0.42	0.42
647 nm	0.31	0.31

TABLE 4. Back-scattering depolarization factor $\delta_L(180^\circ)$ for the JSC-1A lunar simulant retrieved from Eq. 2 and the extrapolated $F_{22}^{au}(180^\circ)$. The results are presented according to the light scattering model used in the extrapolation (Mie or Fraunhofer) and depending on the wavelength (488 nm, 520 nm, and 647 nm).

Database (www.iaa.es/scattering). The data are freely available under citation request of this paper and (Muñoz et al. 2012).

In general, the experimental matrices were very similar at all the studied wavelengths. The results show a behaviour typical for mineral dust. The $-F_{12}(\theta)/F_{11}(\theta)$ ratio shows a red polarization color. This seems to indicate a nearly constant value of the imaginary part of the refractive index at the measured wavelengths (see e.g. Muñoz et al. 2012; Dabrowska et al. 2015).

The measured data were extrapolated at forward and back-scattering, and the asymmetry parameter g and back-scattering linear depolarization factor δ_L were computed from this synthetic matrices. The retrieved linear depolarization ratio varies with wavelength, obtaining values of 0.35, 0.42 and 0.31 at 488 nm, 520 nm, and 647 nm, respectively.

The effect of removing particles smaller than 1 μm in radius on the measured $F_{11}(\theta)$, $-F_{12}(\theta)/F_{11}(\theta)$ and $F_{22}(\theta)/F_{11}(\theta)$ ratios is studied. As the small particles were depleted from the sample due to the filters in the pump system, the forward scattering peak of the phase function became steeper. Further, the maximum of the degree of linear polarization maximum increased, moving toward smaller scattering angles. The negative polarization branch at large scattering angles nearly disappeared after removing the sub-micron fraction from the sample. The $F_{22}(\theta)/F_{11}(\theta)$ ratio was slightly affected in the forward direction and unaffected in back-scattering.

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