An update of the Amsterdam Light Scattering Database

H. Volten\textsuperscript{a,*}, O. Muñoz\textsuperscript{b}, J.W. Hovenier\textsuperscript{a}, L.B.F.M. Waters\textsuperscript{a,c}

\textsuperscript{a}University of Amsterdam, Astronomical Institute "Anton Pannekoek",
Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

\textsuperscript{b}Instituto de Astrofísica de Andalucía, CSIC, c/ Camino Bajo de Huétor 50,
Apartado 3004, 18080 Granada, Spain

\textsuperscript{c}Instituut voor Sterrenkunde, Katholieke Universiteit Leuven,
Celestijnenlaan 200D, B-3001 Heverlee, Belgium

\textsuperscript{*} Corresponding author. Phone: +31205257491. Fax: +31205257484.
E-mail address: hvolten@science.uva.nl

Preprint submitted to Elsevier Science 15 November 2005
Abstract

We present an update of the Amsterdam Light scattering Database located at http://www.astro.uva.nl/scatter. We give a detailed explanation and clarification of the nature of the scattering matrices in the database. Measured scattering matrix elements are presented as functions of the scattering angle, for aerosol particles in random orientation at 632.8 nm. They pertain to seven volcanic dust samples from three different volcanoes, two samples with extreme refractive indices (hematite and rutile), and three forsterite samples with identical compositions, but different size distributions. For fifteen phytoplankton species and two types of silt suspended in water, the database now contains two matrix elements, $F_{11}$ and $-F_{12}/F_{11}$ as functions of the scattering angle at 632.8 nm. Lastly, we have included all scattering matrix elements as functions of the scattering angle for spherical micron-sized water droplets, which may be used for testing purposes.

Key words: Database, light scattering, irregular particles, aerosols, hydrosols, polarization, scattering matrices.

1 Introduction

The Amsterdam Light Scattering Database (http://www.astro.uva.nl/scatter), contains measured scattering matrix elements as functions of the scattering angle for small randomly oriented nonspherical particles in tabular form, so that these data can easily be used in further research. The matrix elements were measured at 632.8 nm and/or 441.6 nm. Whenever available, the database
also includes additional data about the samples such as compositions, refractive indices, SEM pictures, and size distributions. So far most of the data concerned various kinds of irregular silicate particles in air. The database has now been online for a couple of years, and has indeed promoted the use of the measured data in further research, e.g. of remote sensing of the Earth atmosphere [1; 2; 3; 4], theoretical light scattering [5; 6; 7], and astronomy [8; 9].

We have attempted to make the database as complete and self explanatory as possible. In addition, we have explained the use and limitations of the database in an earlier article [10], in particular concerning the size distributions and refractive indices. However, from users of the database we obtained further feedback on how the website could be improved and clarified. This forms the main justification for this paper, since we feel an internet database is not complete without elaboration and clarification in a paper [11].

First, in Sect. 2, we extensively discuss the normalization of the scattering matrix, since we found that a clear understanding of this subject is needed for many applications. Extrapolations of the matrix elements, which are measured between at most 3 and 174 degrees, to scattering angles of 0 and 180 degrees are also discussed in Sect. 2. This extrapolation is necessary for many applications of the data. Second, we briefly present the data included in the database, that are new compared to [10]. These pertain first of all to measurements at 632.8 nm for several aerosol samples, i.e. seven volcanic dust samples.
from three different volcanoes, two samples with extreme refractive indices: hematite and rutile, and three forsterite samples with identical compositions, but different size distributions. Secondly, we give two matrix elements, $F_{11}$ and $-F_{12}/F_{11}$, as functions of the scattering angle at $\lambda = 632.8$ nm for fifteen phytoplankton species and two types of silt suspended in water. Lastly, at the request of some database users, we included in the database results at 441.6 nm and 632.8 nm for all matrix elements of a cloud of spherical water droplets to serve in tests or calibration procedures.

2 The normalization of the scattering matrix

The main purpose of this section is to clarify the meaning of the scattering matrix elements tabulated in the database.

Let us start with considering the following simple scattering experiment [see Fig. 1]. A parallel beam of light is incident on a cloud (ensemble) of randomly oriented particles that scatter the incoming quasi-monochromatic light independently in all directions and without changing the wavelength. Particles and their mirror particles occur in equal numbers. Hence the cloud constitutes a macroscopically isotropic medium with mirror symmetry (see [12, section 2.7]). We assume the cloud to be optically thin so that multiple scattering can be neglected. The light scattered in a direction that makes an angle $\Theta$ (the scattering angle) with the direction of the incident beam is, in general, polarized.
The properties of this scattered light, i.e. the flux and state of polarization, are measured by a detector at a distance, $D$, of the center of the cloud. The plane through the directions of incidence and scattering is called the scattering plane and we use this plane as a plane of reference for defining Stokes parameters as in Van de Hulst [13], Hovenier and Van der Mee [14] and Hovenier et al. [12]. The incident parallel beam of light is characterized by a flux vector $\pi \Phi_0$. This is a column vector with four elements that are Stokes parameters in such a way that the first element is the net flux (irradiance) expressible in Wm$^{-2}$Hz$^{-1}$ or similar units. Similarly the flux vector of the light falling on the detector is the column vector $\pi \Phi$, the first element of which is the net flux detected at a distance $D$.

We can describe the simple experiment by means of the relation [13]

$$\Phi(\lambda, \Theta) = \frac{\lambda^2}{4\pi^2 D^2} F(\lambda, \Theta) \Phi_0(\lambda),$$

where $\lambda$ is the wavelength of the light and $F(\lambda, \Theta)$ is a $4 \times 4$ scattering matrix of the cloud, which depends not only on $\lambda$ and $\Theta$ but also on the number and properties of the scattering particles that contribute to the detected radiation. Another way of describing the simple experiment is by means of the fundamental formula [12, section 2.7]

$$\Phi(\lambda, \Theta) = \frac{N^t C_{sca}(\lambda)}{4\pi D^2} F^{au}(\lambda, \Theta) \Phi_0(\lambda).$$

Here $N^t$ is the total number of scattering particles that contribute to the
detected radiation, $\overline{C}_{sca}(\lambda)$ is their average scattering cross section per particle (average over all $N_t$ particles and orientations) and $F^{au}(\lambda, \Theta)$ is a scattering matrix that is normalized so that the average over all directions of the 1-1 element equals unity. The superscript $au$ is used to indicate this normalization.

The 16 elements of $F(\lambda, \Theta)$ and $F^{au}(\lambda, \Theta)$ are indicated as $F_{i,j}(\lambda, \Theta)$ and $F_{i,j}^{au}(\lambda, \Theta)$, respectively, where $i, j = 1, 2, 3, 4$. Hence we have

$$\frac{1}{4\pi} \int d\Omega F_{1,1}^{au}(\lambda, \Theta) = 1,$$  \hspace{1cm} (3)

where $d\Omega$ is an element of solid angle. Eq. (3) can also be written as

$$\frac{1}{2} \int_0^\pi d\Theta \sin \Theta F_{1,1}^{au}(\lambda, \Theta) = 1.$$  \hspace{1cm} (4)

It should be noted that $F(\lambda, \Theta)$ and $F^{au}(\lambda, \Theta)$ are both called scattering matrices although their normalizations are quite different. Comparing Eqs. (1) and (2) yields the following relationship between these two scattering matrices

$$F(\lambda, \Theta) = \frac{\pi N_t}{\lambda^2 \overline{C}_{sca}(\lambda)} F^{au}(\lambda, \Theta).$$  \hspace{1cm} (5)

The normalization of $F(\lambda, \Theta)$ is now readily obtained from Eqs. (4)-(5). The result is

$$\frac{1}{2} \int_0^\pi d\Theta \sin \Theta F_{1,1}(\lambda, \Theta) = \frac{\pi N_t}{\lambda^2 \overline{C}_{sca}(\lambda)}.$$  \hspace{1cm} (6)

It follows from Eqs. (1)-(2) that all elements of $F(\lambda, \Theta)$ and $F^{au}(\lambda, \Theta)$ are dimensionless. Several other scattering matrices occur in the literature. Differences in normalization are quite common and require special attention.
The same is true for scattering (phase) functions which are the 1-1 elements of scattering matrices.

An advantage of \( F(\lambda, \Theta) \) is its simple additivity property. This means that if a cloud consists of a mixture of \( G \) different subclouds of particles we have for the cloud

\[
F(\lambda, \Theta) = \sum_{g=1}^{G} F_g(\lambda, \Theta),
\]

where the index \( g \) is used to indicate the subclouds. Here the summation can be replaced by integration over a continuous variable characterizing e.g. the size or shape of the particles. Combining Eqs. (5) and (7) we see that the matrices \( F_{au}^g(\lambda, \Theta) \) of subclouds cannot simply be added to get the corresponding matrix of a cloud. Instead we have

\[
F_{au}(\lambda, \Theta) = \frac{\sum_{g=1}^{G} N_{tg} [\overline{C}_{sca}(\lambda)]_g [F_{au}^g(\lambda, \Theta)]_g}{\sum_{g=1}^{G} N_{tg} [\overline{C}_{sca}(\lambda)]_g},
\]

where \( N_{tg} \) is the total number of particles of subcloud \( g \) that contribute to the detected radiation and \( [\overline{C}_{sca}(\lambda)]_g \) is their average scattering cross section per particle. On the other hand \( F_{au}(\lambda, \Theta) \) has the advantage that Eq. (2) shows explicitly how the flux vector of the scattered light at a distance \( D \) depends on the number of participating particles and on their average scattering cross section. \( F(\lambda, \Theta) \) and similar scattering matrices are often used in studies of single light scattering [13; 15], whereas scattering matrices like \( F_{au}(\lambda, \Theta) \), applied to an ensemble of particles in a unit volume, are usually preferred in
multiple scattering studies [12; 16; 17; 18].

If the incident light is unpolarized only the first element of $\pi \Phi_0(\lambda)$ is nonzero. By measuring the net flux of the scattered light for one and the same cloud at various values of the scattering angle, but the same values of $\lambda$ and $D$ and the same net flux of incident unpolarized light, we can readily determine from Eqs. (1)-(2) the ratio

$$\frac{F_{1,1}(\lambda, \Theta)}{F_{1,1}(\lambda, \Theta_0)} = \frac{F^{au}_{1,1}(\lambda, \Theta)}{F^{au}_{1,1}(\lambda, \Theta_0)},$$

(9)

where $\Theta_0$ is a fixed scattering angle. Hence, for a fixed value of $\lambda$ both scattering functions can readily be measured in a relative sense. This means, loosely speaking, that we can measure scattering functions that are normalized to unity at a scattering angle of, for instance, 30 degrees. Note that no knowledge of $N^t$ and $\mathcal{C}_sca(\lambda)$ is needed for this purpose, but care should be taken to keep their product constant while varying the scattering angle or to perform corrections for time variations.

The simple experiment can be continued by changing the state of polarization of the incident beam and analyzing the state of polarization of the scattered radiation. In this way we can obtain the 15 ratios

$$\frac{F_{i,j}(\lambda, \Theta)}{F_{1,1}(\lambda, \Theta)} = \frac{F^{au}_{i,j}(\lambda, \Theta)}{F^{au}_{1,1}(\lambda, \Theta)}$$

(10)

for a fixed value of $\lambda$ and for all values of $i, j = 1, 2, 3, 4$, except $i = j = 1$. Hence the matrix elements with these values of $i$ and $j$ are not determined.
themselves, but only their values relative to the scattering function at the same scattering angle and wavelength. Knowledge of $N^t$ and $C_{sca}(\lambda)$ is not necessary for this.

The simple experiment described above contains the basic features of the more sophisticated experiments that yielded the numbers of the database for a variety of samples. For a more detailed description of these experiments see [19; 20; 21]. Experimental checks on neglecting multiple scattering and the random orientation of the particles have been described in [20]. Thus we obtained the ratios given by Eqs. (9) and (10), where $\Theta_0$ is 30 degrees for all measurements of aerosol particles. For greater clarity the headings of the columns containing numbers for $F_{1,1}(\lambda, \Theta)/F_{1,1}(\lambda, 30^\circ)$ in the database are now $F_{11}/F_{11}(30\text{deg})$ for all aerosol particles and no longer $F_{11}$ as they were in the version of the database discussed by Volten et al [10]. The headings of the columns containing numbers for the ratios of different elements of the scattering matrix, as shown in Eq. (10), have not been changed.

The range of scattering angles in the database is limited to at most 3-174 degrees. Several methods have been developed to extrapolate the data to the full range, in particular for the relative scattering function as given by Eq. (9) (see e.g. [22; 2; 3]). After such an extrapolation has been performed we can first obtain $F_{1,1}^{au}(\lambda, \Theta_0)$ by integration since

$$\frac{1}{2} \int_0^{\pi} d\Theta \sin \Theta \frac{F_{1,1}(\lambda, \Theta)}{F_{1,1}(\lambda, \Theta_0)} = \frac{1}{F_{1,1}^{au}(\lambda, \Theta_0)},$$  \hspace{1cm} (11)
where Eqs. (4) and (9) have been used. Eq. (9) then provides $F_{1,1}^{au}(\lambda, \Theta)$, i.e. the scattering function with the normalization given by Eq. (4), instead of only its ratio to the value at 30 degrees. Finally, the extrapolated values of the ratios given by Eq. (10) can be employed to obtain $F_{i,j}^{au}(\lambda, \Theta)$ for all values of $i, j$ and $\Theta$. The extrapolations to the full range of scattering angles are especially important for multiple scattering computations with or without taking polarization into account.

So far we have considered light scattering by one and the same cloud of particles at various scattering angles but at the same wavelength. Let us now look at data in the database for the same substance at different wavelengths. If we introduce

$$f(\lambda, \Theta) = \frac{F_{1,1}(\lambda, \Theta)}{F_{1,1}(\lambda, \Theta_0)} \quad (12)$$

it is clear that this function equals unity at $\Theta_0$ for all wavelengths, but gener-ally changes with wavelength for other scattering angles. If for some range of scattering angles

$$f(\lambda_1, \Theta) > f(\lambda_2, \Theta) \quad (13)$$

we can rewrite this as (cf. Eq. (9))

$$F_{1,1}^{au}(\lambda_1, \Theta) > \left[ \frac{F_{1,1}^{au}(\lambda_1, \Theta_0)}{F_{1,1}^{au}(\lambda_2, \Theta_0)} \right] F_{1,1}^{au}(\lambda_2, \Theta). \quad (14)$$

Since the expression between square brackets in this inequality was not mea-
sured, it is not tabulated in the database and we cannot conclude from Eq. (14) that $F^a_{1,1}^{au}(\lambda, \Theta)$ is larger or smaller at $\lambda_1$ than at $\lambda_2$ in the range of scattering angles considered. However, by extrapolation we can find $F^a_{1,1}^{au}(\lambda_1, \Theta)$ as well as $F^a_{1,1}(\lambda_2, \Theta)$. In this way we can compare the values at two wavelengths for the same scattering angles. The situation is different for the other scattering matrix elements. Indeed if $F_{i,j}(\lambda, \Theta)/F_{1,1}(\lambda, \Theta)$ is larger at one wavelength than at another the same is true for $F^a_{i,j}^{au}(\lambda, \Theta)/F^a_{1,1}^{au}(\lambda, \Theta)$, as follows from Eq. (10).

By way of example we consider scattering of (unpolarized) sunlight by particles of a comet. We neglect multiple scattering and assume the particles to be in random orientation with equal amounts of particles and their mirror particles. Even if we were to know $F^a_{1,1}^{au}(\lambda_1, \Theta)$ to be larger than $F^a_{1,1}(\lambda_2, \Theta)$ we would not know if the observed flux $\pi \Phi_1(\lambda_1, \Theta)$ is larger than $\pi \Phi_1(\lambda_2, \Theta)$, since this also depends on the wavelength dependence of the average scattering cross sections, the number of participating particles at the time of the observations and the incident flux. But it follows from Eqs (10) and (2) that, if e.g. $F_{2,1}(\lambda, \Theta)/F_{1,1}(\lambda, \Theta)$ is larger at one wavelength than at another, this also holds for $\Phi_2(\lambda, \Theta)/\Phi_1(\lambda, \Theta)$, where the subscripts 1 and 2 refer to the first and second element, respectively, of the observed column vector $\Phi$. This means that the numbers of the database can be used directly for interpreting observations of the wavelength dependence (“color”) of the polarization, but not for comparison with the wavelength dependence (color) of the observed brightness.
3 New samples

The Amsterdam Light Scattering Database has been extended with results for various kinds of particles in random orientation. In this section we first consider particles suspended in air (aerosol particles) and then in water (hydrosol particles).

3.1 Aerosol particles

Since the previous version of the database was put on the web we have published three new papers about measurements performed with the light scattering facility in Amsterdam. The first one of these [23] deals with seven samples of volcanic ashes from eruptions of three different volcanoes, Mount St. Helens, Spurr and Redoubt. The samples were collected at different distances, from a few kilometers up to several hundreds of kilometers from the volcanoes. The scattering matrices of these volcanic ashes samples were measured at a wavelength of 632.8 nm and are now included in the database together with size distributions, information about the origin and composition of the samples, as well as SEM pictures with shape information.

Using these new volcanic ashes measurements and previous volcanic ashes results [24; 25] a Synthetic Average Volcanic Scattering Matrix was constructed, which includes extrapolations to 0 and 180 degrees. This matrix is included
in the database. For the procedure followed to obtain this synthetic matrix, see the database or [23].

Also new in the database are scattering matrix results, and additional information about sizes, shapes and refractive indices, for a hematite and a rutile sample measured at 632.8 nm [26]. These samples of irregular particles are particularly interesting because of their high values of the real part of the refractive index, around 3 and 2.7, respectively. In contrast, their imaginary parts of the refractive index are very different, i.e. $10^{-1} - 10^{-2}$ for hematite and zero for rutile. Their scattering behavior is quite different from that of the irregular silicate particles in the database, and, for certain scattering matrix elements, shows a remarkable agreement with the scattering angle dependence of spherical particles.

Forsterite is detected in many astronomical objects. Measured scattering matrix elements, size distributions, compositions, as well as SEM pictures for three crystalline forsterite samples have been included in the database [27]. These forsterite samples have the same composition, but different size distributions. The differences in sizes and in scattering behavior are small, but may still aid the interpretation of observations of dust in e.g. comets and circumstellar disks.
Light scattering data are at least as scarce for hydrosol particles as for aerosol particles. Yet easily accessible hydrosol light scattering data are essential for remote sensing studies of oceans and lakes, e.g. to establish water quality and assess ecological problems. Therefore, we have included previously measured data for 15 phytoplankton species and 2 types of silts at 632.8 nm [21] in the database. The data pertain to two matrix elements $F_{11}(\Theta)$ and $-F_{12}(\Theta)/F_{11}(\Theta)$ measured from a scattering angle of 20 degrees up to 160 degrees. The values of $-F_{12}(\Theta)/F_{11}(\Theta)$ have not been published in tabular form.

The hydrosol $F_{11}(\Theta)$ functions have been normalized slightly differently from the aerosol $F_{11}(\Theta)$ functions, i.e. they have been scaled at a scattering angle of 90 degrees to a standard function measured for San Diego Harbor water [28], which is indicated as $F11/SDH90$ in the database. To obtain the same normalization as for the aerosol particles, it suffices to divide all values of $F_{11}/SDH90$ of a hydrosol by its value at 30 degrees. The values of $-F_{12}(\Theta)/F_{11}(\Theta)$ remain the same.

Phytoplankton particles can have exotic shapes and a lot of internal structure. This not only strongly influences their scattering behavior, but also complicates determining their size distributions and complex refractive indices. Various methods were used to obtain estimates for these quantities. These methods are mentioned in the database. In particular, when Mie-theory was
applied to obtain estimates for the size distribution or refractive index given in the database, these estimates may not be very reliable. Therefore, the user of the database should use these estimates with care.

4 Test particles

In the database we now provide all matrix elements as functions of the scattering angle of micron-sized water droplets in air, measured at 441.6 nm and 632.8 nm [10]. As for the aerosol particles the first column contains values of $F_{1,1}(\lambda, \Theta)/F_{1,1}(\lambda, 30^\circ)$. Since for such homogeneous spherical particles we can compare the measured data with results of Mie-calculations, these measurements were performed to calibrate and test the setup. We did not include these data in the database before, since the results are almost perfectly reproducible by using Mie-theory for homogeneous spheres with the refractive index of water. However, we learned that this also renders the data useful in tests of methods in which measured data, including error bars, are used as input, see e.g. [4].

5 Concluding remarks

We hope that the new additions to the database and the clarification of the nature of the measured scattering matrices will evoke new applications of
the data provided, whether this is in the field of theoretical light scattering, astronomy, studies of planetary atmospheres, or other fields. We intend to implement new improvements and to provide new input for the database.

Acknowledgments

We are indebted to all people who provided feedback. In particular, we are grateful to Timo Nousiainen, Oleg Dubovik, and Michael Mishchenko for providing good ideas. To Michael Mishchenko we are furthermore grateful for his comments on an earlier version of this paper. We would like to thank Rohied Mokiem, Mike Lankamp, and Alfons Hoekstra for their support in building and maintaining the website. Lastly, we would like to thank Martin Konert of the Free University of Amsterdam for conducting laser diffraction measurements of size distributions.

References


[9] M. Min, J. W. Hovenier, A. de Koter, Shape effects in scattering and


Fig. 1. A light source emits a parallel beam of quasi-monochromatic light. This light is scattered by a cloud of small randomly oriented particles in air or a liquid. A detector at a distance, $D$, of the cloud receives light scattered in a direction given by the scattering angle, $\Theta$, and measures its net flux and state of polarization. The detector can be moved along a circle with radius $D$ within a certain range of scattering angles.