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On the size distribution functions and their application in regolith studies

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Abstract

The knowledge of particle size distribution (PSD) of regolith surfaces on terrestrial planets, their satellites and minor bodies, has an important role in the field of remote sensing and the study of regolith evolution. Various mathematical distribution functions (dfs) which are currently in use to describe regolith PSD, have been compared on the basis of their best fitting with terrestrial and lunar samples. The correspondences of parameters of the dfs with known physical characteristics of the samples have also been analyzed so that a distribution function suitable for practical applications can be obtained. Rosin's distribution comes out to be one which can be fitted to both terrestrial and lunar samples with confidence (LSSE/data < 0.003), and also numerically obtained physical parameters from the distribution are close to the sample values (errors $< 10\%$ on average).

Keywords: Planets and satellites: surfaces; Methods: data analysis

1. Introduction

In the analysis of cometary polarization data, it is now evident that the particle size distribution (PSD) of the icy dust grains produced due to sublimation of comet's surface material has an important role on the nature of polarization phase curves (e.g. Sen et al., 1991; Das and Sen 2006). In the study of planetary surfaces however it is not clearly known if size distribution of regolith particles significantly alters remote sensing data, it is evident from previous studies that the albedo strongly depends on the average particle diameter of a regolith surface (Nelson et al., 2000; Kaasalainen 2003; Piatek 2003 etc.). Since size distribution plays an important role in the single scattering of light from an ensemble of particles well separated from each other (Hansen and Travis 1974), it should have some influence on the behavior of the scattered light from regolith where multiple scattering is involved.

Study of PSD is also important in the study of planetary regolith samples because these retain signatures of various evolutionary processes that these have passed through during a long period after their formation. For example, a fresh crater ejecta has a much skewed PSD towards larger particle sizes which is completely different from a mature regolith PSD (McKay et al.1974). Further, immature lunar samples show bimodality in their distribution, whereas mature lunar regolith samples are not bimodal in nature (Clark et al., 2002). Again, a regolith sample can have fractional maturity, i.e. combination of two distributions of different phase of maturity, which can be modeled if parent distributions are known (McKay et al.,1974). Also, owing to different location and environment in the solar system, PSD of regolith may significantly vary from object to object depending on the history of evolution. Regolith is produced due to meteorite and micrometeorite impact on atmosphere-less bodies. A recent study suggests that

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fragmentation of rocks larger than a few centimeters due to diurnal temperature variation may also take a dominant part in regolith formation (Delbo et al., 2014). Due to similar history of evolution, mercurian and lunar regolith known to have similar nature but with a slight variation in PSD - as implied by remote sensing results (Dollfus and Auriere (1974)). It is also evident that, lunar breccias (which is formed from regolith) are quite fine grained and the number of particles rapidly decreases as particle size is increased, whereas meteoritic breccias (which originated at asteroids) in general have coarser grains and quite a flat size distribution (Housen and Wilkening 1982) which is probably due to the different environment of regolith development. On the other hand, regolith on bodies which are covered by atmosphere like Mars may have been produced due to a variety of processes such as cratering, volcanism, erosion of bedrock by fluvial and/or Eolian mechanism and consequently expected to have different PSD for each. Although Lognormal and Modified gamma distributions have been used to characterize Martian regolith, differences in PSD for above cases are not well understood yet and there are disagreements among scientists (Soderblom 2007; Pollack, Ockert-Bell and Shepard 1995; Santee and Crisp 1993; Toon et al., 1977). In particular in the case of Mars, the mean diameter for regolith produced by cratering, flood deposits, pyroclastic deposits, weathering products and Eolian drift deposits should have characteristic values of 0.5–10 mm, 8–50 mm, 0.08–4 mm, 0.1–5 mm, 0.01–0.03 mm (Gooding, 1981). Due to these differences, PSD of regolith on bodies covered by atmosphere may not be described by a single distribution function. As regolith development on airless bodies are chiefly due to meteoritic impact – those distributions which are used for application in case of mechanically crushed material (like Rosin's law) may be generally applicable.

Normally, Gamma distribution (Section 2) is applied when the PSD is fine and confined within a narrow range of particle diameter and Log-normal distribution is preferred when range of particle size is quite large. Mishchenko (1992) used Gamma distribution to study optical properties of the outer solar system icy objects (for fine particles with effective radius $\sim$1 μm and effective variance = 0.04), Mishchenko et al. (1999) used the same for soil surface of effective radius = 10 μm and effective variance = 0.1. From lunar perspective we shall see in this work, Rosin's distribution (Section 2) fits better than Gamma distribution for powders with effective radius a few microns and effective variance < 1. On the other hand, Martin and Mills (1977) showed less than 1 mm size fraction of lunar regolith can be comfortably fitted with Rosin's law but with a discontinuity in the distribution. It will be seen in this work, less than 1 mm size fraction of three distinct lunar regolith samples can be best fitted by a Log-normal distribution rather than Rosin's law by a small margin, but this hardly affects outcome of the analysis.

Apart from above, PSD study of finest fraction of regolith has some astro-biological importance also. It may create respiratory and other biological problems in a human body which can be important for future manned planetary missions (Park et al., 2008).

From all above, it becomes clear that study of the nature of regolith size distribution is an important subject in planetary surface studies and therefore various mathematical distribution functions (summarized in Section 2) are used for remote sensing analysis and modeling calculations of PSD. Main difficulty with the use of these distribution functions (dfs) is that these include some adjustable parameters which control the nature of PSD, but their correspondence to the physical parameters of regolith (such as effective diameter, effective variance and mode) are not well established yet on the basis of experimental samples of known parameters. On the other hand, since PSD of regolith can be of wide variety owing to different nature of the parent body and processes of regolith formation, all these distribution functions may not be equally applicable in all cases. It is therefore important to find out which distribution function will suit most a particular kind of regolith and how do the function parameters correspond to the physical parameters of a regolith size distribution.

Present study concentrates on a comparative study of some popular dfs and their parameters in contrast with the known physical parameters of some experimental samples of different origin by best fitting the curves with experimental data. Most of the used samples have d_{eff} (effective diameter) in the range - a few micrometers to a few tens of micrometers, and v_{eff} (effective variance) in the range $\sim$1 to 10 (Section 3), which are typical for regolith of planetary and asteroidal origin. Apart from these, three fine fraction lunar soils (less than 1 mm sized) and two finest fractions (lunar dusts, less than about 20 μm) from Apollo missions have also been studied.

2. Distribution functions

Experimental analysis of lunar regolith samples and other natural dust samples reveal that the particle size distributions of such samples have a much skewed nature towards smaller particle sizes. Roughly these PSDs are log-normal in character; however Log normal distribution fails to fit all PSD curves with satisfaction (King and Butler 1977). Therefore, other distribution functions have been proposed and are being used by researchers for remote sensing analysis. These are described in Table 1 below as a function of particle radius r.

where $n(r)$ is the fractional number of particles per unit volume of space per unit radius range at radius r, and K is a normalizing constant in all above cases such that

$$\int_0^\infty n(r)dr = 1 \tag{5}$$

Mathematically, Gamma distribution (Eq.(1)) parameter $a \approx r_{eff}$ (effective radius) and $b \approx v_{eff}$ (effective variance) (Hansen and Travis 1974) if Eq. (5) is satisfied and $b \in [0,0.5)$. In Modified gamma distribution (Eq. 2) the