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A spherical Monte-Carlo model of aerosols: Validation and first applications to Mars and Titan

Mathieu Vincendon [a,b,*], Yves Langevin [b,1]

[a] Department of Geological Sciences, Brown University, Providence, RI 02912, USA
[b] Institut d'Astrophysique Spatiale, Université de Paris Sud 11, 91405 Orsay, France

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ABSTRACT

The atmospheres of Mars and Titan are loaded with aerosols that impact remote sensing observations of their surface. Here we present the algorithm and the first applications of a radiative transfer model in spherical geometry designed for planetary data analysis. We first describe a fast Monte-Carlo code that takes advantage of symmetries and geometric redundancies. We then apply this model to observations of the surface of Mars and Titan at the terminator as acquired by OMEGA/Mars Express and VIMS/Cassini. These observations are used to probe the vertical distribution of aerosols down to the surface. On Mars, we find the scale height of dust particles to vary between 6 km and 12 km depending on season. Temporal variations in the vertical size distribution of aerosols are also highlighted. On Titan, an aerosols scale height of 80 ± 10 km is inferred, and the total optical depth is found to decrease with wavelength as a power-law with an exponent of −2.0 ± 0.4 from a value of 2.3 ± 0.5 at 1.08 µm. Once the aerosols properties have been constrained, the model is used to retrieve surface reflectance properties at high solar zenith angles and just after sunset.

1. Introduction

Mars and Titan's atmospheres are permanently loaded with aerosols. Typical optical depths in the visible and near-IR wavelengths range between 0.2 and 10 as a function of location, season and wavelength (Pollack et al., 1977; Smith et al., 1981; Lemmon et al., 2004; Smith, 2004; Tomasko et al., 2008). Algorithms for separating the surface and aerosol contributions are therefore frequently used when analyzing a Mars or Titan dataset obtained by remote sensing (Clancy and Lee, 1991; Erard et al., 1994; McCord et al., 2006; Rodriguez et al., 2006; Vincendon et al., 2007). The radiative transfer codes widely used in surface–atmosphere separation problems assume a plane-parallel geometry (Stamnes et al., 1988; Evans, 1998). This approach is relevant when the solar zenith angle is small enough to neglect the curvature of the planet (typically less than 80° for Mars and 65° for Titan, which has a larger relative scale height). Beyond that limit, the use of spherical codes is required (Collins et al., 1972; Adams and Kattawar, 1978; Herman et al., 1994). The high solar zenith angles encountered around the terminator increase the effective optical depth of aerosols, which prevents the use of simplifying single scattering approximations such that followed by Santer et al. (1986). So far, only Monte-Carlo methods are able to take into account the planetary curvature without simplifying assumptions on multiple scattering (Blättner et al., 1974; Oikarinen et al., 1999; Tran and Rannou, 2004; Pitman et al., 2008). However, spherical Monte-Carlo algorithms are time-consuming and have been mainly used for limited planetary data processing (Whitney et al., 1999; Lebonnois and Toublanc, 1999; Vasilyev et al., 2009) or for validation purpose (Tran and Rannou, 2004; Tomasko et al., 2008).

In this paper we describe and implement a fast 3D Monte-Carlo algorithm of radiative transfer through particles in a spherical, laterally homogeneous atmosphere and include the surface–atmosphere interface. Our approach takes advantage of the symmetry of homogeneous spheres by reducing the problem to a 1D atmosphere and surface (but with 3D photometric/radiative transfer effects) in order to reduce the computational time. This modeling approach can be compared to observations when the "independent pixel approximation" is relevant, i.e. when all photons collected by an instrument looking at a given location are the result of radiative transfer in atmospheric and surface properties representative of this location. This requires that aerosols and surface properties do not significantly vary over lateral distances from one to several atmospheric scale heights (i.e., typically around 10 km for Mars and 60 km for Titan). The first section of this paper describes the equations of the Monte-Carlo algorithm. The model is then applied to observations around the terminator obtained by OMEGA/Mars

* Corresponding author. Address: Department of Geological Sciences, Brown University, 324 Brook Street, Box 1846, Providence, RI 02912, USA. Fax: +1 401 863 2058.

E-mail addresses: mathieu_vincendon@brown.edu (M. Vincendon), yves.langevin@ias.u-psud.fr (Y. Langevin).

[1] Fax: +33 1 69 85 86 75.

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