Icarus 223 (2013) 1–10

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Radiative transfer modelling of dust devils

Jonathon P. Mason *, Manish R. Patel, Stephen R. Lewis

The Open University, Walton Hall, Milton Keynes MK7 6AA, United Kingdom

ARTICLE INFO

Article history:
Received 13 June 2012
Revised 16 November 2012
Accepted 16 November 2012
Available online 2 December 2012

Keywords:
Earth
Mars
Mars, Atmosphere
Atmospheres, Dynamics

ABSTRACT

Dust devils are particle laden convective vortices that form at the base of convective plumes. They are typically observed in dry desert climates on Earth and have been observed to form frequently on Mars. Meteorological measurements have also indicated that martian surface spacecraft have experienced numerous dust devil transits. To date, the characterisation of dust devils through the interpretation of spectral measurements of sunlight taken during a transit has yet to be investigated. Such measurements would provide valuable information of the physical size, dust load and internal structure of dust devils. A Monte Carlo Radiative Transfer (MCRT) model was developed to simulate the attenuation of sunlight through a dust devil and to investigate the observed spectral variation during such an event. The predicted transit signature resulting from a dust devil transit is highly dependent on the method of observation. The scattered light flux increases during the transit with the magnitude dependent on the dust concentration, making it sensitive to the internal dust distribution. This dependence is not observed for the total light flux which experiences a decrease and is strongly dependent on the total extinction through the vortex and insensitive to how the dust is distributed. The implication of this work is that separate *in situ* measurement of both the total *and* scattered flux is crucial for characterising dust devils and such measurements provide a powerful tool that could be exploited by future Mars missions.

1. Introduction

Aeolian mineral dust can have a large impact on the radiation budget of planetary atmospheres such as those surrounding the Earth and Mars. This dust can absorb solar and infrared radiation resulting in localised warming of the atmosphere (positive radiative forcing) and scatter incoming electromagnetic radiation back to space, resulting in cooling of the atmosphere (negative radiative forcing). The balance between absorption and scattering determines whether the aeolian dust acts to cool or warm the surrounding atmosphere (Alpert et al., 1998) and highlights the importance of accurate retrieval of the dust particle single scattering properties, specifically the single scattering albedo (ω_0), defined as the ratio of the scattered solar radiation to the total solar radiation removed by both scattering and absorption. One method used to retrieve the single scattering properties is to fit the observed attenuated spectrum to radiative transfer model outputs. However, accurate modelling of the light transmission through a dusty environment can be extremely difficult, especially at high dust concentrations, where the single scattering approximation is inadequate to accurately describe the diffuse component. The Monte Carlo Radiative Transfer (MCRT) method has been used successfully in many different fields to accurately describe multiple scattering scenarios in significantly different environments. Witt (1977) applied MCRT to interstellar grains by looking at reflectance nebulae and has shown that MCRT can be applied to the multiple scattering problem. MCRT was employed by Vincendon and Langevin (2010) to simulate the impact of aerosols on the remote sensing of the surface of Mars and Titan. More relevant to this study, Metzger et al. (1999) used a MCRT to simulate the scattered diffuse component of martian dust devils observed by the Imager for Mars Pathfinder (IMP).

The purpose of this paper is to describe a MCRT model that is used to simulate the transmission of sunlight through dust devil vortices. The simulated spectral variation during a dust devil transit over a spectrometer is investigated to determine whether the dust load, size and internal structure of the vortex can be estimated from a dust devil transit signature (defined as the measured light curve as a function of distance). The transmission of sunlight through the vortex depends on how the dust is distributed internally and the internal structure of the vortex (in terms of the core diameter). Therefore the internal structure and dust distribution of dust devils is explored explicitly, comparing the assumption of a uniform dust concentration to one with a relatively dust free central vortex surrounded by walls of a higher dust concentration. Finally, the effect on the transit signature due to variations in the entrained dust particle single scattering properties is investigated to determine the possibility of retrieval of the dust particle optical properties. Dust devils have yet to be characterised by interpreting

* Corresponding author.
E-mail address: j.p.mason@open.ac.uk (J.P. Mason).

0019-1035/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2012.11.018

in situ spectral measurements and this will be an invaluable technique for martian surface landers, which experience hundreds of dust devil transits during their life but may be unable to provide images of all encounters to determine their physical parameters.

This paper discusses previous retrievals of aeolian dust optical properties on Earth and investigations into the characteristics of terrestrial and martian dust devils. The developed MCRT model is described, followed by an analysis into the photon propagation through the model volume for different dust concentrations and optical scattering properties. Finally, the predicted transit signatures of dust devils with different internal structures and dust distributions are provided and the effects of changes to the dust single scattering properties discussed.

1.1. Airborne desert dust on Earth

The optical properties of airborne terrestrial dust remains a debated issue (Dubovik et al., 2000; Kaufman et al., 2001). Expressed in terms of its imaginary refractive index, n_i, (a measure of the amount electromagnetic radiation absorbed by the material) the recognised value by the World Meteorological Organisation (WMO) is 0.008 at 500 nm (WMO, 1983) and corresponds to a single scattering albedo (ω_0) of 0.63. Another study by Levin et al. (1980) predicted a smaller n_i of 0.003 ($\omega_0 \sim 0.87$). For desert dust, ω_0 has been simulated to have values between 0.63 and 0.87 at 500 nm (Shettle and Fenn, 1976; WMO, 1983; Hess et al., 1998). To exacerbate the issue, Fouquart et al. (1987), using aircraft radiation measurements, determined an ω_0 value for the broadband solar spectrum to be 0.95 for Saharan dust, indicating significantly less absorption. Furthermore, recent retrievals of ω_0 for desert dust (Dubovik et al., 2000; Kaufman et al., 2001) agree with the results of Fouquart et al. (1987) with $\omega_0 > 0.9$ for the majority of the solar spectrum, indicating that the dust acts to cool the atmosphere. It should be recognised that the uncertainty in the retrieved single scattering properties is likely due to natural variability resulting from heterogeneity in the dust material at different global locations. This also applies at local spatial scales where the composition of the source material can vary significantly. The large uncertainty in the single scattering properties of suspended desert dust can lead to contrasting predictions of their radiative forcing, with a small change in ω_0 from 0.95 to 0.85 leading to positive radiative forcing instead of negative forcing (Hansen et al., 1997). This highlights the importance of accurate determination of ω_0 at visible wavelengths. Dust devils are efficient at lofting small particles into the atmosphere (Greeley et al., 2006) and therefore knowledge of the dust optical properties and the amount of material lofted into the atmosphere enables the radiative effect of dust devils on the local atmosphere to be determined.

1.2. Dust devils

Dust devils are low pressure, warm core vortices which usually occur during the summer season in arid locations around the world (Ives, 1947). A dust devil is a special type of vertical convective current characterised by dust entrained around the upward convective flow. Many in-depth field studies of terrestrial dust devils have been carried out to date (Sinclair, 1966, 1974; Ryan and Carroll, 1970; Metzger, 1999; Greeley et al., 2003; Balme and Greeley, 2006).

Laboratory experiments have also been conducted to investigate different components of dust devil vortices. Greeley et al. (2003) constructed a vortex generator (The Arizona State University Vortex Generator, ASUVG) to simulate terrestrial and martian dust devils. Their experiments showed that the pressure drop (ΔP) at the vortex core provides an additional lift component, making dust devils more efficient at removing dust from surfaces than boundary layer winds. Using the ASUVG, Neakrase et al. (2006) and Neakrase and Greeley (2010a) conducted dust and sediment flux experiments at Earth and Mars atmospheric pressures and found that the sediment flux is related to the vortex intensity, which itself is dependent on the ΔP at the core. Their experiments showed that vortices of different sizes could yield the same ΔP at the core and concluded that the vortex size is less important for sediment lifting than the ΔP at the core. The vertical flux of dust (particles <2 μm in diameter) was found to increase exponentially with increasing tangential velocity but decrease exponentially with increasing core radii demonstrating that smaller vortices experience higher vertical dust fluxes. A similar relationship to the core pressure drop was also reported with an exponential increase in vertical dust flux for larger ΔP. Furthermore, the effects of surface roughness on dust devil dynamics was explored by Neakrase and Greeley (2010b) for terrestrial and martian dust devils. They found a correlated increase in the vortex size with increasing surface roughness, while the tangential velocity was observed to decrease. The expansion of the vortex reduces the energy available and will eventually impede additional lifting of surface material. However, Neakrase and Greeley (2010b) showed that small increases in surface roughness can reduce the threshold required to lift fine particles (<100 μm), enhancing the sediment flux of weaker dust devils beyond that which would be expected. For larger increases in surface roughness the ΔP and tangential velocities are reduced, decreasing the vertical flux of surface material. While the theoretical modelling presented in this paper focuses on the applications to field studies, measuring the light flux through laboratory generated dust devils would allow investigations into the effect of dust particle size on the spectral attenuation and how the size of the particles being suspended influences the spatial distribution of dust in the dust devil interior. Since the dust particle size and the physical dimensions of laboratory generated dust devils can be constrained, these measurements would be more directly comparable to model predictions than those taken in the field.

Dust devils are not a unique phenomenon to the Earth, with observations from Viking 1 and 2, Mars Pathfinder (MPF), Mars Global Surveyor, Odyssey and Mars Exploration Rovers (MER), among others, showing that they form frequently on the martian surface (Ryan and Lucich, 1983; Thomas and Gierasch, 1985; Metzger et al., 1999; Ferri et al., 2003; Fisher et al., 2005; Cantor et al., 2006; Greeley et al., 2010). While dust devils on the two planets are similar, they play very different roles on their respective planets. On Earth they are secondary to boundary layer winds in the dust cycle and only play a minor role except possibly in arid regions. In contrast, on Mars they maintain the constant aeolian dust background, especially in northern summer, and play a major role in the rapid transport of fine particulates into the martian planetary boundary layer, affecting the atmospheric heating rate. Dust devils also influence the surface albedo through the formation of tracks as they transverse the surface (Balme et al., 2003; Whelley and Greeley, 2006). From column opacity measurements taken by IMP, Metzger et al. (1999) estimated the particle loading for a dust devil to be 70 mg m^{-3} and, assuming a vertical wind velocity of 7 m s^{-1}, they determined the vertical flux of material into the atmosphere to be 0.49 g m^2 s^{-1}. Using the thermodynamic theory for dust devils of Rennó et al. (1998) and MPF meteorological data, Ferri et al. (2003) estimated the vertical velocity of martian dust devils to be 20 m s^{-1} and determined the rate at which dust is injected into the atmosphere by dust devils to be two orders of magnitude higher than the dust settling rate. The Mars Exploration Rover (MER) Spirit observed three full seasons of dust devil activity within Gusev crater during Mars years (MY) 27, 28 and 29 (Greeley et al., 2010). Over all seasons the vertical wind speeds of the dust devils were observed to be between 0.04 and 17.0 m s^{-1} with the vertical dust flux ranging between 0.004 and 0.46 g m^2 s^{-1}.