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# Self-generated clouds of micron-sized particles as a promising way of a Solar Probe shielding from intense thermal radiation of the Sun

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ABSTRACT

An effect of shielding of an intense solar radiation towards a solar probe with the use of micron-sized SiC particles generated during ablation of a composite thermal protection material is estimated on a basis of numerical solution to a combined radiative and heat transfer problem. The radiative properties of particles are calculated using the Mie theory, and the spectral two-flux model is employed in radiative transfer calculations for non-uniform particle clouds. A computational model for generation and evolution of the cloud is based on a conjugated heat transfer problem taking into account heating and thermal destruction of the matrix of thermal protection material and sublimation of SiC particles in the generated cloud. The effect of light pressure, which is especially important for small particles, is also taken into account. The computational data for mass loss due to the particle cloud sublimation showed the low value about 1 kg/m$^2$ per hour at the distance between the vehicle and the Sun surface of about four radii of the Sun. This indicates that embedding of silicon carbide or other particles into a thermal protection layer and the resulting generation of a particle cloud can be considered as a promising way to improve the possibilities of space missions due to a significant decrease in the vehicle working distance from the solar photosphere.



## 1. Introduction

The complex physical effects in the solar photosphere and also in the vicinity of the Sun have attracted the interests of numerous researchers during many years. A series of space missions are planning including the suggested NASA project “Solar Probe Plus” with the launch in 2018 [1–5]. It is especially important to make the observations and measurements from relatively small distances from the sun. One of the main technical problems to be solved for the success of such a mission is an acceptable thermal regime of the probe equipment at very high thermal radiation flux from the sun (see Fig. 1). The ordinary ablating thermal protection may be insufficient to reach a desirable duration of the mission. Therefore, it is important to find a novel method to protect the solar probe from the intense solar irradiation.

One of the possible ways of attenuation of the solar radiation can be based on the use of micron-sized particles generated by an advanced thermal protection material during the matrix ablation. This principal solution to the thermal protection problem is expected to be more promising than the use of special reflecting coatings [4] at extremely small distances from the photosphere. The latter statement is examined in the paper.

A weakly absorbing substance of particles seems to be preferable, but it does not help to decrease the radiation absorption in the particle cloud because of multiple scattering [6,7]. The preliminary calculations showed that a high melting temperature and relatively low sublimation rate of solid particles at high temperatures are the decisive advantages. At the same time, the dielectric particles, which are semi-transparent in the visible and near-infrared spectral ranges have additional advantage because they do not prevent propagation of microwave radiation for both the remote sensing and transfer of obtained data to a host vehicle at the Earth orbit. In the present paper, we consider silicon carbide as a good preliminary choice for the particle substance. The main thermal and optical characteristics of this substance and particles

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**Nomenclature**

| | |
|---|---|
| $a$ | particle radius |
| $c$ | specific heat capacity |
| $D$ | radiation diffusion coefficient |
| $d$ | thickness of particle cloud |
| $E$ | energy, normalized spectral coefficient |
| $F$ | radiation source function |
| $f_v$ | volume fraction of particles |
| $G$ | spectral irradiation |
| $I$ | spectral radiation intensity |
| $L$ | latent heat of sublimation |
| $M$ | molecular mass, mass of the cloud |
| $\dot{M}$ | total mass sublimation rate |
| $\dot{m}$ | mass sublimation rate |
| $n$ | index of refraction |
| $Q$ | efficiency factor |
| $q$ | radiative flux |
| $R$ | radial distance, gas constant |
| $T$ | temperature |
| $t$ | time |
| $W$ | volumetric radiation power |
| $z$ | normal coordinate |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | absorption coefficient |
| $\beta$ | extinction coefficient |
| $\delta$ | width of size distribution |
| $\kappa$ | index of absorption |
| $\lambda$ | radiation wavelength |
| $\bar{\mu}$ | asymmetry factor of scattering |
| $\rho$ | density |
| $\sigma$ | scattering coefficient |
| $\Phi$ | size distribution of particles |
| $\omega$ | scattering albedo |

*Subscripts and superscripts*

| | |
|---|---|
| 0 | initial, universal |
| a | absorption |
| b | blackbody |
| Arr | Arrhenius |
| int | integral |
| m | mean |
| min | minimum |
| max | maximum |
| n-h | normal-hemispherical |
| p | particle |
| s | scattering |
| sat | saturation |
| SiC | silicon carbide |
| sol | solar |
| tr | transport |
| w | wall |
| $\lambda$ | spectral |

of SiC will be considered below. Silicon carbide is characterized by very weak absorption in the main part of the solar spectrum and also by a relatively low sublimation rate. At the same time, we do not exclude possible use of other substances of particles.

The problem of radiation propagation in a cloud of small particles is physically similar to that considered in fire protection [8–10] and also in a particular problem of attenuation of solar radiation using water mists and sprays [11]. Of course, the absence of atmosphere around the space vehicle simplifies the problem because there is no complex convection typical of water sprays

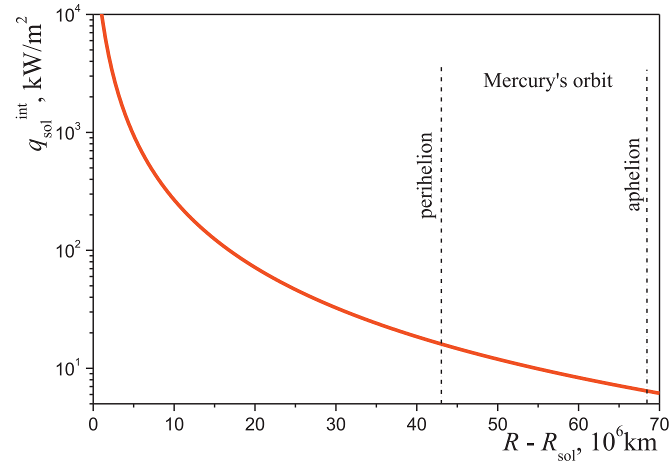


**Fig. 1.** Integral solar radiative flux as a function of the orbit radius.

[12,13]. On the other hand, the problem to be solved is much more complicated because of strong feedback effects in heat transfer and complex dynamical and thermal behavior of particles.

The objective of the present paper is two-fold: (1) to develop a relatively simple but physically sound model for the radiative and combined heat transfer in a cloud of SiC particles taking into account the generation of particles and their complex motion and (2) to obtain the main estimates which are important for possible recommendation of the new concept of Solar Probe shielding from solar thermal radiation and subsequent consideration of this approach as a basis of promising engineering solutions to the thermal protection problem for space vehicles.

The central problem of this analysis is a spectral radiative transfer through a cloud of absorbing and scattering particles, but this key problem is considered together with the coupled processes of both the thermal destruction of the matrix of composite protection material and the sublimation of SiC particles. The effect of complex motion of particles under both the drag force from gases generated during the thermal protection ablation and the light pressure, which is especially important for partially sublimated micron-sized particles is also estimated in the paper.

As in many papers on radiation in heat transfer problems, the details of scattering phase function of single particles can be neglected, especially in the case of multiple scattering. Moreover, even in the case of optically thin layer of a scattering medium, the effect of anisotropic scattering of radiation by particles can be described using the so-called transport approximation. The simplest transport approximation mentioned in early book by Davison [14] appears to be highly successful method to solve many applied problems [7,10,11,15–19]. According to this approximation, the scattering function is replaced by a sum of the isotropic component and the term describing the peak of forward scattering. A good accuracy of this approach in solving the combined heat transfer problems is explained by the use of integral (over the angles) characteristics of the radiation field such as the radiative flux (in the boundary conditions) and its divergence (in the energy equation). Therefore, the transport characteristics of scattering are considered below in an analysis of spectral optical properties of particles.

## 2. Optical properties of SiC particles

Consider first the data for spectral optical constants of silicon carbide. It is known that this substance is characterized by a very low absorption in the visible and near-infrared [20–23], i.e. in the spectral range of the most powerful thermal radiation of the Sun. The quantitative information on index of refraction, $n$, and index