Icarus 257 (2015) 9–22

Contents lists available at ScienceDirect

Icarus

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

Coma dust scattering concepts applied to the Rosetta mission

Uwe Fink [a,*], Giovanna Rinaldi [b]

[a] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, United States
[b] IAPS-INAF, via del Fosso del Cavaliere, 100, 00133 Roma, Italy

ARTICLE INFO

Article history:
Received 19 August 2014
Revised 13 March 2015
Accepted 3 April 2015
Available online 20 April 2015

Keyword:
Comets, coma

ABSTRACT

This paper describes basic concepts, as well as providing a framework, for the interpretation of the light scattered by the dust in a cometary coma as observed by instruments on a spacecraft such as *Rosetta*. It is shown that the expected optical depths are small enough that single scattering can be applied. Each of the quantities that contribute to the scattered intensity is discussed in detail. Using optical constants of the likely coma dust constituents, olivine, pyroxene and carbon, the scattering properties of the dust are calculated. For the resulting observable scattering intensities several particle size distributions are considered, a simple power law, power laws with a small particle cut off and a log-normal distributions with various parameters. Within the context of a simple outflow model, the standard definition of $Af\rho$ for a circular observing aperture is expanded to an equivalent $Af\rho$ for an annulus and specific line-of-sight observation. The resulting equivalence between the observed intensity and $Af\rho$ is used to predict observable intensities for *67P/Churyumov–Gerasimenko* at the spacecraft encounter near 3.3 AU and near perihelion at 1.3 AU. This is done by normalizing particle production rates of various size distributions to agree with observed ground based $Af\rho$ values. Various geometries for the column densities in a cometary coma are considered. The calculations for a simple outflow model are compared with more elaborate Direct Simulation Monte Carlo Calculation (DSMC) models to define the limits of applicability of the simpler analytical approach. Thus our analytical approach can be applied to the majority of the *Rosetta* coma observations, particularly beyond several nuclear radii where the dust is no longer in a collisional environment, without recourse to computer intensive DSMC calculations for specific cases. In addition to a spherically symmetric 1-dimensional approach we investigate column densities for the 2-dimensional DSMC model on the day and night side of the comet. Our calculations are also applied to estimates of the dust particle densities and flux which are useful for the in-situ experiments on *Rosetta*.

1. Introduction

In an earlier paper (Fink and Rubin, 2012), we developed and discussed relationships that connected the observable measure of the dust output, $Af\rho$ (A'Hearn et al., 1984), to its dust production rate and mass loss rate. We extend and clarify our methods in this paper to calculate line-of sight column densities and scattered light intensities for use in the analysis and interpretation of the dust environment of Comet 67P/Churyumov–Gerasimenko, (abbreviated to 67P) the target of the Rosetta space mission (e.g. Glassmeier et al., 2007). Most of our work was carried out during a visit of Giovanna Rinaldi to Tucson, AZ.

Our analysis is based on an analytical approach rather than using computer modeling e.g. the code SCATRD (Vasil'ev, 2006). While a computer model can take into account effects such as multiple scattering, or 3D atmospheres they often contain assumptions and approximations that are not well understood or documented. It is important that their results be compared to the output of analytical determinations which can be more easily calculated and verified.

We will be closely guided by the Direct Simulation Monte Carlo Calculation (DSMC) for cometary gas (Tenishev et al., 2008) and for the dust outflow (Tenishev et al., 2011). These simulations provide the acceleration of the dust particles by the evaporating gas, their velocities and spatial densities. They can also yield the dust distribution for a spherical nucleus as a function of latitude for a two dimensional model where one hemisphere is illuminated by sunlight and the other hemisphere is in darkness. The DSMC model, however, does not provide the absolute amount of dust lifted off a nucleus surface i.e. its production rate, nor the size distribution of the dust. To overcome this shortcoming we develop relationships that connect the production rate of the dust, observable column densities and scattered light intensities to the commonly used

* Corresponding author.

http://dx.doi.org/10.1016/j.icarus.2015.04.005
0019-1035/

measure of a comet's dust output $Af\rho$, applying a variety of particle size distributions which, to a large extent determine the overall dust scattered light intensity. Additionally, we find that the majority of the *Rosetta* coma observations can be analyzed with sufficient accuracy using our analytical approach, without requiring to run specific DSMC cases, which are very computer intensive.

We concentrate on the remote sensing imaging spectrometer VIRTIS (Coradini et al., 2007), and the imaging cameras OSIRIS (Keller et al., 2007). However, our analysis is also useful for the in-situ dust sensing instruments GIADA (Colangeli et al., 2007), MIDAS (Riedler et al., 2007), COSIMA (Kissel et al., 2007) and the remote sensing microwave instrument MIRO (Gulkis et al., 2007).

The remote sensing instruments will measure the line of sight (LOS) intensity of scattered sunlight $I(\lambda, \rho, g)$, as a function of wavelength (λ), impact parameter (ρ) and phase angle (g) for various geometries of the nucleus environment of the comet. It is a fairly complex process to use these data to gain an understanding of fundamental properties of cometary dust that we are interested in:

(a) The column density of the dust and from this quantity the dust mass loss rate of the whole nucleus, and thus the dust/gas mass ratio.
(b) Constraints on the composition of the dust via its wavelength dependence.
(c) Constraints on the dust particle size distribution mostly by observing the phase dependence of the scattered radiation.
(d) The correlation between active areas and dust jets and a better understanding of the mechanism of dust production and dust lift off.
(e) The dust evolution as a function of the comet's heliocentric distance.

2. Observable single scattering intensity $I(\lambda)$ for a column of particles

Our objective is to obtain a dust column density and the properties of the dust from the observed intensity and thus we start with the observable light intensity, $I(\lambda)$, for single scattering and confine ourselves, for the present, to a single particle size, a. The expression, given below contains five quantities, which are described in turn.

$$I(\lambda) = \mathcal{F}_i(\lambda) n_{col}(\rho) \sigma_{geom} q_{sca}(\lambda) \frac{p(g)}{4\pi}$$

$\mathcal{F}_i(\lambda)$ is the solar flux at the comet at a particular wavelength. It is given by $\frac{F_s(\lambda)}{r_h^2}$ where r_h is the heliocentric distance in AU of the comet from the Sun and $F_s(\lambda)$ is the solar flux at 1 AU (e.g. Neckel and Labs, 1984).

$n_{col}(\rho)$ is the column density observed by the spacecraft. Calculation of that is not simple and a detailed description of this is given below.

σ_{geom} is the geometric cross section of each particle. It is straightforward to calculate for spherical particles.

$q_{sca}(\lambda)$ is the scattering efficiency of each particle. This is a function particle size and composition. We use Mie scattering and an index of refraction of $n = 1.70 + 0.02i$, and give the rationale for this below.

$p(g)$ is the phase function for a particular particle size. It is normalized so that $\int_{4\pi} p(g) d\Omega = 4\pi$. For isotropic scattering $p(g) = 1$. The phase function is calculated for each particle size from Mie scattering using the above index.

Determination of the column density for the highly non-uniform coma of a comet is non-trivial and requires a detailed discussion which is given in the next section. The column density can be calculated using a simple spherical outflow model or using the more complex Direct Simulation Monte Carlo code, or DSMC model (Tenishev et al., 2011). An additional complication is the particle size distribution since the observed intensity combines the contributions from all particles. This will be addressed in Section 5. For purposes of illustration, we pick a wavelength of 1.0 μm which is in the middle of the VIRTIS instrument wavelength range, and a phase angle of 40°. Our formulation can readily be extended to other wavelengths, phase angles and other non-uniform column densities.

2.1. Scattering properties of the dust particles

The last three quantities of the above equation contain the scattering properties of the dust particles which can be collected into an expression S_d, which is a function of their size, their composition as expressed by their complex index of refraction, n, the wavelength, λ, the phase function, and the shape of the particles.

$$S_d(a, n, \lambda, g) = \sigma_{geom} q_{sca}(\lambda) p(g)$$

At present we do not have a good idea what the most appropriate scattering properties for the dust particles should be since we only have a rough idea of their shapes, and their composition. For the calculations in this paper, we used Mie scattering for spherical particles, although we expect the dust particles to be fluffy aggregates made up of many small particles. Modeling of relatively compact and spherical but porous interstellar grains (Voshchinnikov et al., 2005) and porous grains in debris disks (Kirchschlager and Wolf, 2013) have shown that the curves for the scattering, absorption and extinction efficiencies as a function of particle size and wavelength are only marginally different from calculations for Mie particles. Similar results were found in comparisons with laboratory measurements by Pollack and Cuzzi (1980) for scattering of randomly oriented particles possessing a variety of shapes, sizes and refractive indices.

It is likely however, that larger differences will be encountered for cometary fluffy open aggregates made up of many small particles. At present we do not have scattering efficiencies available for such particles. It appears that with improving computing power, such efficiencies may become available using techniques such as Discrete Dipole Approximation or the multi-sphere T-matrix approach (e.g. Kolokolova and Mackowski, 2012). When such data become available to us we plan to substitute these values for our present "approximate" Mie scattering values.

2.2. Estimate of an effective index of refraction

Analysis of *Cometary* Interplanetary Dust Particles (IDP's), the so called "Chondritic Porous IDP's" collected by high altitude aircraft (Bradley, 2003; Keller and Messenger, 2011), show that they are mostly primitive silicates with roughly 10% carbonaceous material. This number is slightly lower than the value of ~22% of the grain population having grains dominated by carbon and/or organic matter found for Comet 1P/Halley by Fomenkova et al. (1994). Both the pyroxenes and the olivines are of the Mg rich (or Fe poor) type. It is thought that pyroxene is more abundant than olivine, (Keller, private communication). The organics consist of graphite as well as complex organic molecules. Dynamical calculations for the zodiacal dust by Nesvorný et al. (2010) indicate that very likely 90% of these particles are of cometary origin so that the IDP's should serve as a good proxy for the composition of dust particles in the coma of a comet. Samples of coma collected by the Stardust spacecraft to Comet 81P/Wild 2 (Zolensky et al., 2006) corroborate this, finding that their composition is quite similar to that of anhydrous chondritic IDP's and composed mainly of Fe poor pyroxene