DOI: 10.1478/C1V89S1P008

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 89, Suppl. No. 1, C1V89S1P008 (2011)

PHYSICAL PROPERTIES OF COMETARY DUST FROM MONTE CARLO ANALYSIS OF TAIL AND COMA IMAGES

FERNANDO MORENO*

(Invited paper)

ABSTRACT. Forward and inverse Monte Carlo modeling of cometary dust tail and coma images has provided one of the best approaches to infer the basic physical dust parameters and their time dependence: mass loss rates, ejection velocities, and size distribution functions. These methods attempt to fit the brightness distribution found in cometary astronomical images at a variety of wavelengths. The trajectories and the light scattered by the dust particles are functions of the size parameter, shape, and refractive index. In this paper we describe briefly the Monte Carlo technique, and present some applications.

1. Introduction

Dust grains embedded in the cometary ices are dragged out by the vacuum expansion of the gases coming from sublimation of the ices. The ice sublimation depends on the nature of the ice and the heliocentric distance. When comets approach perihelion, the outgassing is greatest, giving rise to dust comae and tails. The detailed hydrodynamical processes that take place in the circumnuclear coma region are very complex, and depend, among other things, on the nucleus surface heterogeneity and topography [2]. For the purposes of interpretation of the dust tails and comae, a number of boundary conditions must be assumed. Thus, the dust ejection velocities are assumed to be the terminal velocities of the grains when they are already decoupled from the gas drag. The size distribution is very broad, with particles in the submicrometer to the centimeter range.

The Monte Carlo process involves the computation of (i) the orbit and position of the ejected particles in the so-called sky or photographic plane, and (ii) the contribution of the light scattered by each particle to the total brightness of the tail or coma.

2. Orbital computations

Once the dust grains are submitted to space, they experience a number of forces. For small-sized cometary nuclei (most nuclei are of order $\sim$ 1 km), the nucleus gravity becomes negligible, and the most important contributions are the pressure radiation force, and the solar gravity force. Long-term effects, such as the Poynting-Robertson drag force, or the Yarkovsky effect, are ignored.

The radiation pressure force exerted on a particle is proportional to the radiation efficiency pressure vector $\overrightarrow{Q_{pr}}$. For non-spherical particles this quantity is a full three-dimensional vector. The radial (Sun-to-comet) component of $\overrightarrow{Q_{pr}}$ as a function of particle size for astrosilicate material [3] is displayed in Figure 1 for irregular particles (DW1996, see [5]), oblate spheroids (T-matrix calculations with Mishchenko's code [14], and spheres. From this graph, it is seen that the assumption of spherical particles constitutes a fair approximation for computation of the radial component of $\overrightarrow{Q_{pr}}$.

The non-radial over radial radiation pressure efficiency ratio depends on size, shape, orientation, refractive index, and the state of rotation of the grain. Calculations on ellipsoids [11] and aggregate particles [12], as well as experimental data [13] show that these non-radial terms may be as large as 30% or more of the radial component at some size parameters. However, since the particles are surely rotating with unspecified rotation periods and axis orientations, these non-radial components would be in practice very difficult to obtain. Thus, the non-radial components are neglected.

The equation of motion of the dust grain in case the non-radial pressure force is neglected becomes very simple, as it then describes the motion of a particle in a reduced solar gravity field by the β parameter, defined as the ratio of radiation pressure force to solar gravity force. Consequently, the particle describes a keplerian orbit. The position of the ejected grain must be calculated in the photographic plane (N, M) [6].

3. Light scattering computations

The light we observe from comets is overwhelmingly singly-scattered light from dust released from the surface of the comet nucleus. The surface itself does not contribute significantly unless the comet is almost inactive. In these conditions, the contribution of the scattered light by each individual grain to the total brightness of the tail at the phase angle of the observations, in a given (N, M) location of the image, is a function of the phase function p and the scattering cross section C_{sca}, both functions of particle size, shape, and refractive index. The dependence of phase function on grain size represents a major problem from the resonant to the geometric optics limit due to the high computational times and memory requirements with the current light scattering codes. An observational estimate of this quantity was derived from Giotto spacecraft encounter with comet Halley, p=0.04. In the same way that the radial component of $\overrightarrow{Q_{pr}}$, the assumption of sphericity is adequate for computations of Q_{sca} (see Figure 1).

4. Previous achievements and future prospects

The procedure described above, with the indicated limitations, has been used by various authors to extract physical properties of cometary dust. Since the early work of Finson and Probstein [6], and their application to comet Arend-Roland [7], the most significant improvement has been made by Fulle [10], who incorporated the Monte Carlo approach with an inverse method. This method has been used to obtain the dust environment of a number of comets (e.g. [9] and references therein), and by Moreno (see e.g. [15]). The direct technique described above has been recently implemented by Fulle et al. [8] to study the dust environment of comet 67P/Churyumov-Gerasimenko in preparation for

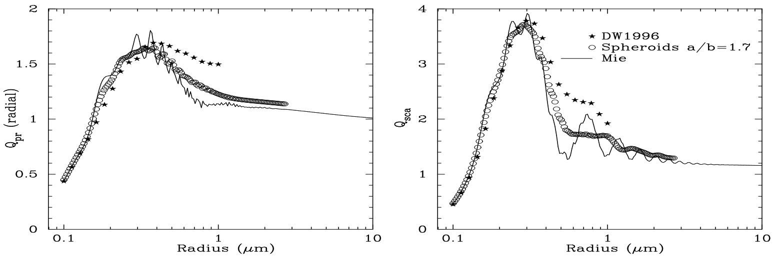

Figure 1. The radial component of the radiation pressure efficiency vector (left) and the scattering coefficient (right) as a function of the effective radius, for irregular particles (DW1996, [5]), averaged over 125 orientations, oblate spheroids of a/b=1.7, and spheres of astrosilicate refractive index at λ=0.6 μm.

the forthcoming Rosetta mission arrival in 2014. Figure 2 represents a comparison of the results from three different codes, built by Fulle (e.g. [9]), Agarwal et al. [1] (who used an analytical approach), and Moreno [15]. This agreement among the results emphasizes the validity of the different approaches used.

Another field of application of the Monte Carlo code is related to the interpretation of polarimetric images. Since from the simulations of the dust tail brightness we know the size distribution in each pixel of the image, we can also retrieve the linear polarization for incident unpolarized light at that location, providing a polarimetric map. Thus, if there are available simultaneous images of intensity and linear polarization, we can impose additional constraints to the tail fit procedure. The problem again is the range of intermediate size parameters. In this regard, experimental light scattering measurements, such as those we are currently performing in our Cosmic Dust Laboratory ([16, 17]) will be of most importance.

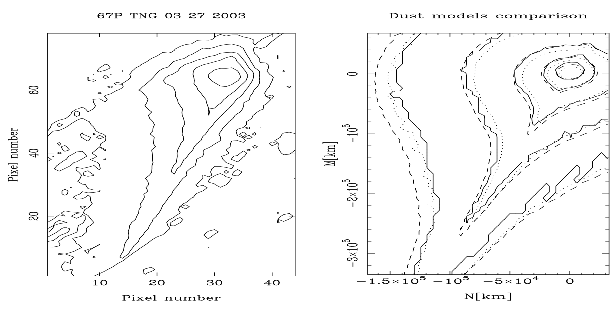

Figure 2. Left panel: Image of comet 67P obtained through a red filter at the 3.6-m Telescopio Nazionale Galileo at La Palma on March 27, 2003. Right panel: Simulations using an isotropic ejection model: Solid lines: Trieste model [9] Dashed lines: Analytical approach [1]; Dotted lines: Granada model [15]. Isophotes vary in factors of 2 between levels [8]

.

Acknowledgments

This work was supported by contracts P09-FQM-4555 and AYA2009-08190.

References

[1] Agarwal, J., Müller, M., Reach, W.T., Sykes, M.V., Boehnhardt, H., and Grün, E., "The dust trail of Comet 67P/Churyumov-Gerasimenko between 2004 and 2006", *Icarus*, **207**, 992, (2010).

[2] Crifo, J.F., "Multidimensional physicochemical models of the near-nucleus coma: Present achievements and future developments", *Advances Space Res.*, **38**, 1911, (2006).

[3] Draine, B.T., and Lee, H.M., "Optical properties of interstellar graphite and silicate grains", *ApJ*, **285**, 89, (1984).

[4] Draine, B.T., and Flatau, P.J., "User Guide to the Discrete Dipole Approximation Code DDSCAT 7.1", http://arxiv.org/abs/1002.1505v1.

[5] Draine, B.T., and Weingartner, J.C., "Radiative Torques on Interstellar Grains. I. Superthermal Spin-up", *ApJ*, **470**, 551, (1996).

[6] Finson, M.L., and Probstein, R.F., "A theory of dust comets. I. Model and Equations", *ApJ*, **154**, 327, (1968).

[7] Finson, M.L., and Probstein, R.F., "A theory of dust comets. II. Results for comet Arend-Roland", *ApJ*,**154**, 353, (1968).

[8] Fulle, M., et al. (15 co-authors), "Comet 67P/Churyumov-Gerasimenko: the GIADA dust environment model of the Rosetta mission target", *Astron. Astrophys.*, **522**, 63 (2010).

[9] Fulle, M., " Motion of Cometary Dust", in *Comets II*, M. Festou, U. Keller, and H. Weaver eds., University of Arizona Press, Tucson, USA (2005).

[10] Fulle, M., "Evaluation of cometary dust parameters from numerical simulations - Comparison with an analytical approach and the role of anisotropic emissions", *Astron. Astrophys.*, **217**, 283, (1989).

[11] Il'in, V.B., and Voshchinnikov, N.V., "Radiation pressure on non-spherical dust grains in envelopes of late-type giants", *Astron. Astrophys. Suppl. Ser.*, **128**, 187, (1998).

[12] Kimura, H., Okamoto, H., and Mukai, T., "Radiation pressure and the Poynting-Robertson effect for fluffy dust particles", *Icarus*, **157**, 349, (2002).

[13] Krauss, O., and Wurm, G., "Radiation pressure forces on individual micron-size dust particles: a new experimental approach", *J. Quant. Spectrosc. Rad. Transfer*, **89**, 179, (2004).

[14] Mishchenko, M.I., Capabilities and of a current FORTRAN implementation of the T-matrix method for randomly oriented, rotationally symmetric scatterers. *J. Quant. Spectrosc. Rad. Transfer*, **60**, 309, (1998).

[15] Moreno, F., "The Dust Environment of Comet 29P/Schwassmann-Wachmann 1 From Dust Tail Modeling of 2004 Near-Perihelion Observations", *ApJS*, **183**,33, (2009).

[16] Muñoz, O., Moreno, F., Guirado, D., Ramos, J. L., López, A., Girela, F., Jerónimo, J. M., Costillo, L. P., Bustamante, I., "Experimental determination of scattering matrices of dust particles at visible wavelengths: The IAA light scattering apparatus", *J. Quant. Spectrosc. Rad. Transfer*, **111**, 187, (2010).

[17] Muñoz, O., Moreno, F., Guirado, D., Ramos, J. L., Volten, H., and Hovenier, J. W., "The IAA cosmic dust laboratory: Experimental scattering matrices of clay particles", *Icarus*, **211**, 894, (2011).

---

* Instituto de Astrofísica de Andalucía
Solar System Department
Glorieta de la Astronomía, s/n
Granada 18008, Spain

Email: fernando@iaa.es

Paper presented at the ELS XIII Conference (Taormina, Italy, 2011), held under the APP patronage; published online 15 September 2011.
