Dynamics of Cometary Dust

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Abstract. This paper summarizes recent progress in our understanding of the morphological diversity of dust comets. This diversity is a product of dust emission from discrete active areas on the nucleus surface and provides information on the comet's rotation state and source function. Advances in computer simulations of dust coma morphology are described and the diagnostic properties of various dusty features are emphasized. Also addressed are some of the issues of dust tail morphology and particle fragmentation. Finally, lessons learnt from investigations of the dust population of comet Shoemaker- Levy 9 are discussed and implications for physical studies of the comet's collision with Jupiter are identified.

1. Introduction

Although a variety of features (jets. fans, spirals, etc.) was observed visually in the near-nucleus region of a number of comets during the 19th century, serious attempts to interpret and model them dynamically began only in the 1970s and 1980s, respectively. Reviewed by Sekanina (1581), the pioneering efforts aimed at elucidating dust coma morphology led to the conclusion that activity from the nuclei of many, especially short-period, comets originates in discrete emission areas and that the appearance of observed features is determined by the surface distribution of active regions, by the mode of emission, and by the nucleus rotation state. Restricted initially to mere *contour fitting* to observed features (Sekanina & Larson 1984, 1986a, h), this modelling soon developed into increasingly successful *Monte Carlo image simulation* (Sekanina 1987a,b, 1988).

A parallel line of attack involved dynamical interpretations of structures in cometary dust tails. While *streamers* have long been understood as products of major, temporally isolated episodes of dust emission from the nucleus, competing theories existed to explain relatively rare *striae* (for a review, see, e.g., Sekanina 1980). As described in Sec. 3.2, advances since the late 1980s have significantly accelerated the research in this field.

One commonality shared by nearly all structures in the dust coma and tail of comets is the optical dominance by micron- and submicron-sized grains subjected to appreciable accelerations by solar radiation pressure, of up to ~2.5 times the solar gravity. However, comet Shoemaker - Levy 9 (1994 X = 1)/1993 F2), now defunct, differed dramatically from other comets both in its appearance and in properties of the dust content of the essentially structureless condensations, dominated by pebble-sized and larger particulates (Sec. 4).

2. Recent Computer Simulations of Dust Coma Morphology

Major progress has been achieved since the latest review (Sekanina 1991a) of these simulation activities. First of all, the fundamental parameters of the synthetic images--- which include the nucleus spin axis orientation and the rotation period at the time of dust emission, the surface locations of dust sources, and the range of particle ejection velocities and accelerations due to solar radiation pressure- were expanded to encompass two additional constants that allow one to introduce random perturbations into the computer-simulated motions of dust particles. One of the constants, α_1, describes the magnitudes of particle-trajectory perturbations that are independent of particle residence length in the coma, the other, α_2, characterizes the effects that scale with the length. The results, examples of which are exhibited in Figure 1, show that inclusion of random effects substantially enhances the model's capabilities for generating synthetic images that faithfully simulate the observed appearance of dust comets. Of particular interest is the fact that by increasing the magnitude of the perturbations, it is possible gradually to "erase" any morphological feature, as shown on the images in the bottom row and the rightmost column of the figure. This implies that distinct morphology in a comet's head is diagnostic of *collimation* of dust particle flow from active sources and that the lack of morphology is *not* necessarily an indicator of the absence of any such sources.

The question of collimation is closely related to the problems of activity from concave topographic features, such as craters and other depressions. For comets, effects of topography were studied by Colwell & Jakosky (1987) and by Colwell *et al.* (1990), and, from another standpoint, by Keller *et al.* (1994). Colwell *et al.* find that the sublimation rates from the floors of craters are always higher than from their walls and that there is a natural tendency for material driven from a crater to be collimated. Keller *et al.* confirm increased collimation of flow from local depressions, but conclude-- from comparison of their hydrodynamic calculations with the distribution of light in dust jets imaged with the Halley Multicolor Camera (HMC)---that the observations can be explained by relatively shallow depressions, of a diameter-to-depth ratio of about 6:1. They also find that dust driven by a coverging gas flow above inactive patches surrounded by an active area, a cone.e]jt, independently proposed by Whipple (1983), can explain the strongly collimated '[filaments') seen on the HMC images of Halley's near-nucleus environment to be superimposed on the broader and much brighter jets (Thomas & Keller 1987). Keller *et al.* (1994) admit, however, that more realistic, three-dimensional models of the dust flow are necessary before major conclusions can be made on the morphology and topography of the nucleus surface. More pronounced depressions, of a diameter- to-depth ratio of less than two, were inferred by Sekanina (1991b) for discrete sources on the nucleus of P/Tempel 2 from information on the comet's water production curve and other extensive evidence from ground-based observations.

Very recently, the image simulation software was further substantially upgraded to account for short-term (diurnal) variations in the production rate of dust from an active source and to accommodate a great variety of particle-size distribution laws (Sekanina 1993). This new capability is particularly helpful when modelling rapidly changing morphological features emanating from the nucleus during a comet's major outburst.

COMPUTER GENERATED IMAGES OF A SYSTEM OF SPIRAL JETS

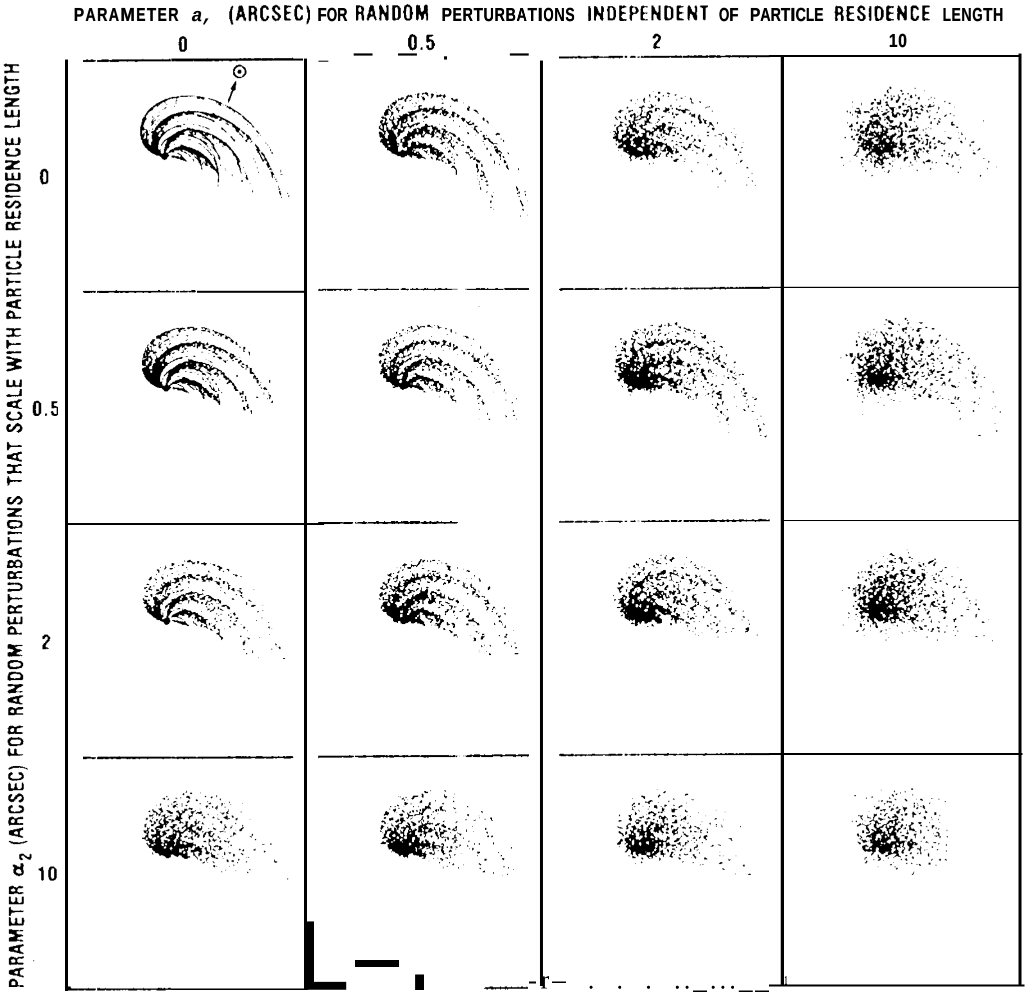

Figure 1. Computer generated images of a dust coma consisting of spiral jets, imitating the appearance of comets such as Bennett (1970 II = C/1969 Y1). All images were generated with identical reference parameters, except for the two randomization constants, α_1 and α_2. The random effects that are independent of particle residence length in the coma increase in the images from the left to the right, the effects that scale with the length increase in the images from the top to the bottom, α_2 being their characteristic angular magnitude at 1 arcmin from the nucleus. The image in the upper left corner ($\alpha_1 = \alpha_2 = 0$) shows the direction to the Sun and consists of particle loci that are entirely ‘(unperturbed”. In order to appreciate the values of the constants α_1 and α_2 it should be mentioned that each box is about 100 arcsec on a side.

3. Dust Tail Morphology, Its Modelling, and Particle Fragmentation

A basic property of cometary dust tails is that they preserve an "imprint" of the history of dust emission for a limited period of time. This information can be recovered, sometimes with a surprisingly high temporal resolution.

3.1. Streamers

Streamers are relatively common, fairly narrow, and rectilinear or somewhat curved bands or rays in the dust tail, emanating from the coma. As products of brief enhancements of dust production (outbursts) or suddenly increased variations in diurnal activity, they have long been known to represent true *synchronic* formations. The orientation of a streamer is diagnostic of the time of outburst and its length provides information on the peak radiation pressure acceleration (or its lower bound) to which the ejects were subjected.

During the past decade, the simple synchrone-fitting technique was applied to several comets and most notably to early post-perihelion, large-scale images of comet Halley (1986 111 = 11'/1982 U1), separately by Lamy (1986), by Sekanina (1986), and by Beisser & Boehnhardt (1987 a, b). At least 6 to 8 streamers were identified, all emitted within two weeks of perihelion, at times when the comet had been optically unobservable from Earth because of its conjunction with the Sun. The independently derived emission times agree to within a fraction of one day and provide valuable information on the comet's activity.

3.2. Striae

Unlike streamers, striae are bands that appear in dust tails less commonly, are always separated from the coma by huge gaps, their orientations are inconsistent with those of synchronic formations, have a tendency to cluster into pairs or groups, almost never aim at the nucleus, and when extended beyond their visible length, they interesct the radius vector mostly on the sunward side of the nucleus. Their nature had long remained unexplained and even today they are not fully understood, in spite of the intensified research since the 1960s.

Two competing models emerged out of these efforts: Notni's (1964) high-speed particle-ejection theory, which was originally applied to comet Mrkos (1957 V = C/19S71'1), and Sekanina & Farrell's (1980) particle fragmentation theory, first tested on comet West (1976 VI = C/1975 V1). Notni proposed that the motions of striae are determined by strong coupling between dust ejects and comet plasma, which results in "terminal" particle-ejection velocities of 10 km/s or more in a tailward direction near the nucleus. On the other hand, Sekanina & Farrell explained the striae as formations composed of fragments of parent particles that had been ejected in an outburst, subjected to the same, rather high, radiation pressure acceleration during their motion through the tail, and subsequently fragmented at the same time. For comet Mrkos, Sekanina & Farrell (1982) found two kinds of striae that consisted, respectively, of absorbing and dielectric grains. Akabane (1983) employed an essentially identical approach (but a different terminology) in his study. Comparing the two competing models, Notni & Thänert (1988) confirmed that the fragmentation theory is consistent with the motions of striae in both Mrkos and West, but found that the high-speed ejection theory fails for West. The fragmentation model was also successfully applied to comet Seki-Lines (1962 111 = C/1962 C1) by Nishioka & Watanabe (1990) and preliminary results are available for comet 1910 I (= C/1910 Al) (Sekanina & Farrell 1986). Nishioka & Watanabe (1990) concluded that the constraint on the fragmentation time of parent particles can be relaxed, if the fragments have finite lifespans. The constraint on the parents' radiation pressure acceleration remains, however, firm, which implies that their source might in fact be a single massive piece so extremely porous as to be optically thin, a property that is dictated observationally by the high acceleration values,

An additional argument in favor of the fragmentation theory of the striae is strong independent evidence on fragmentation processes in comets. Space allows me to mention only one particularly fitting case: vigorous dust fragmentation was necessary, according to Utterback & Kissel (1990), to explain a cloud of highly friable attogram grains at large distances from Halley's comet, detected with particle-impact ion mass spectrometers onboard three spacecraft.

4. Dust in Comet Shoemaker- Levy 9

This comet displayed four kinds of morphological feature. The brightest part was the **nuclear t7'sin,** containing all the condensations. Extending from the train on either side were *trails* or *wings*. Pointing generally to the west and subtending a moderate angle (~20 30°) with tile train was a set of parallel, rectilinear *tails*, whose roots coincided with the condensations. The tails were immersed in an enormous structureless sector of material, which was stretching to the north of its sharp boundary delineated by the train and the two trails.

It was shown elsewhere (Sekanina *et al.* 1994, Sekanina 1995a) that the sector was made up of microscopic particles, that the *smallest* grains in the tails observed soon after discovery were ~ 150 μm across (but much larger in July 1994), that they were released from the comet most probably between early July and the end of 1992, and that their initial velocities did not exceed 0.4 m/s. Since each tail was an outgrowth of its parent condensation, particles in the train must have been still larger and their velocities still lower. No evidence exists for dust emission during 1993- 94 and quantitative estimates as low as 200 g/s were derived for its upper limit (Sekanina 1995a).

The sizes and dynamics of particulate material in the condensations have been subject to much controversy. From considerations of radiation pressure effects, the minimum particle diameter in a condensation's innermost region, up to ~2000 km from its center, is estimated at 1- 2 meters in January --July 1994, at an assumed density of 0.2 g/cm3. From the observed brightness and assuming a geometric albedo of 0.04, the mass of debris (up to subkilometer-sized boulders) in an average condensation is estimated at 10’^{4} to $10^{15.5}$ grams, depending on the mass distribution law. This is still less than the mass of any one of the largest fragments that, were detected digitally on the Hubble Space Telescope images (Sekanina 1995b). in any case, there is no doubt whatsoever that the debris in Shoemaker- Levy 9-- unlike in most comets- consisted of large-sized, extremely slow] y moving particulate that accounted for all the light from the nuclear train.

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