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Morphology of Cometary Dust Coma and Tail

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Abstract. This paper summarizes some 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 large-scale 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, constraints on the mass, size, and velocity field of the dust population of comet Shoemaker–Levy 9 are set from the object's morphological observations in 1993–94.

1. Introduction

Although a variety of features (jets, fans, spirals, etc.) was observed visually in the dust coma of a number of comets during the 19th century, serious attempts to interpret and model dynamically the coma's large-scale morphology began only in the 1970s and 1980s, respectively. Reviewed by Sekanina (1981), the pioneering efforts aimed at understanding this morphology led to the conclusion that activity of comets, especially of the short-period ones, originates in discrete emission sources on their nuclei and that the appearance of observed features depends on the surface distribution of the sources, the mode of emission, and the nucleus rotation state. Restricted initially to mere *contour fitting* of the features (e.g., Sekanina & Larson 1984, 1986a,b), this work soon developed into increasingly successful *Monte Carlo image simulation* (Sekanina 1987a,b, 1991a).

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 large-scale 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 = D/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

Closeup images of Halley's nucleus, particularly those taken with the Giotto's *Halley Multicolour Camera* (HMC), convincingly document dust jets streaming away from discrete sources on the sunlit side of the nucleus (Keller *et al.* 1987), as predicted by the computer-simulation model (Sekanina & Larson 1984). Since the latest review of these modelling efforts (Sekanina 1991a), the parameters of the synthetic images—which include the nucleus spin vector at the time of dust emission, the surface dust-source distribution, and the range of particle ejection velocities and accelerations due to solar radiation pressure—were expanded to introduce random noise into the computer-simulated motions of dust particles (Sekanina 1991b), using two constants: α_1, which describes the noise that is independent of the particle residence length in the coma, and α_2, which characterizes the noise that scales with the length. The results, examples of which are exhibited in Figure 1, show that the inclusion of noise substantially enhances the model's capability to generate synthetic images that faithfully simulate the observed coma appearance of dust comets. Of considerable interest is the fact that by increasing the noise, it is possible gradually to "erase" any morphological feature, as illustrated in the figure's bottom row and its rightmost column. This implies that while large-scale morphology of a comet's head indeed is a product of *collimation* of dust particle flow from discrete active sources, the lack of this 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 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 converging gas flow above inactive patches surrounded by an active area, a concept independently proposed by Whipple (1983), can explain the strongly collimated "filaments" seen on the HMC images 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 (1991c) 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.

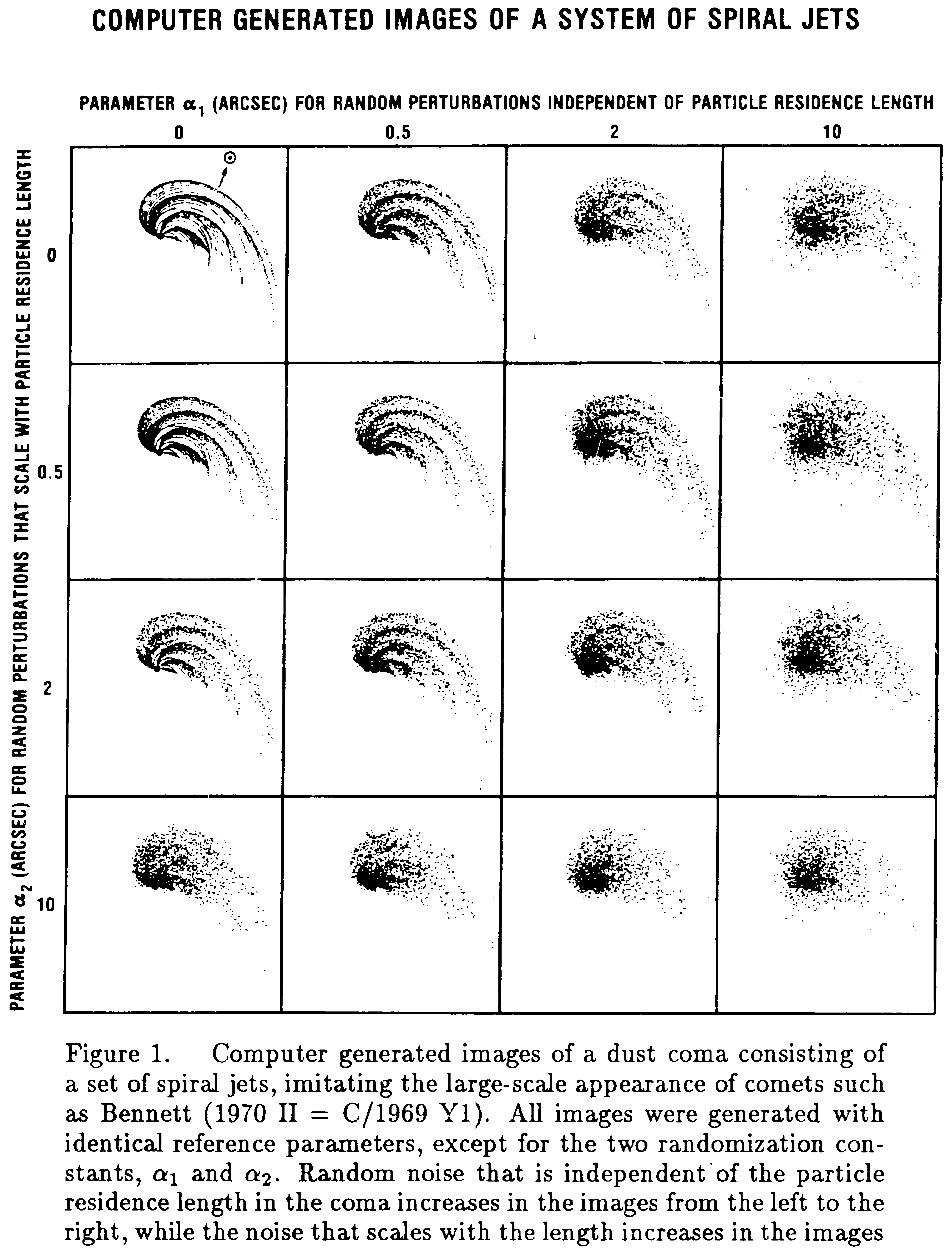

Figure 1. Computer generated images of a dust coma consisting of a set of spiral jets, imitating the large-scale appearance of comets such as Bennett (1970 II = C/1969 Y1). All images were generated with identical reference parameters, except for the two randomization constants, α_1 and α_2. Random noise that is independent of the particle residence length in the coma increases in the images from the left to the right, while the noise that scales with the length increases in the images from the top to the bottom, α_2 characterizing this noise at 1 arcmin from the nucleus. The image in the upper left corner ($\alpha_1 = \alpha_2 = 0$), which shows the direction to the Sun, consists of noiseless particle loci. The meaning of the constants α_1 and α_2 is explained in the original investigation; the relation of their values to the image's scale can be appreciated by pointing out that each box is about 100 arcsec on a side. (From Sekanina 1991b.)

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 ejecta 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 III = 1P/1982 U1), separately by Lamy (1986), by Sekanina (1986), and by Beisser & Boehnhardt (1987a,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 intersect 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/1957 P1), 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 ejecta 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 III = C/1962 C1) by Nishioka & Watanabe (1990) and preliminary results are available for comet 1910 I (= C/1910 A1) (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 train*, 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 the 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/cm^3. 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^{14} 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 slowly moving particulates that accounted for all the light from the nuclear train.

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References

Akabane, T. 1983, PASJ, 35, 565

Beisser, K. & Boehnhardt, H. 1987a, in Diversity and Similarity of Comets, E. J. Rolfe & B. Battrick, Noordwijk: ESTEC, 665

Beisser, K. & Boehnhardt, H. 1987b, Ap&SS, 139, 5

Colwell, J. E. & Jakosky, B. M. 1987, Icarus, 72, 128

Colwell, J. E., Jakosky, B. M., Sandor, B. J. & Stern, S. A. 1990, Icarus, 85, 205

Keller, H. U. *et al.* 1987, A&A, 187, 807

Keller, H. U., Knollenberg, J. & Markiewicz, W. J. 1994, Planet. Sp. Sci., 42, 367

Lamy, P. 1986, Adv. Space Res., 5, No. 12, 317

Nishioka, K. & Watanabe, J.-i. 1990, Icarus, 87, 403

Notni, P. 1964, Veröff. Sternw. Babelsberg, 15, No. 1

Notni, P. & Thänert, W. 1988, Astr. Nachr., 309, 133

Sekanina, Z. 1980, in Solid Particles in the Solar System, I. Halliday & B. A. McIntosh, Dordrecht: Reidel, 237

Sekanina, Z. 1981, Ann. Rev. Earth Planet Sci., 9, 113

Sekanina, Z. 1986, IAUC No. 4187

Sekanina, Z. 1987a, in Diversity and Similarity of Comets, E. J. Rolfe & B. Battrick, Noordwijk: ESTEC, 315

Sekanina, Z. 1987b, in Diversity and Similarity of Comets, E. J. Rolfe & B. Battrick, Noordwijk: ESTEC, 323

Sekanina, Z. 1991a, in Comets in the Post-Halley Era, R. L. Newburn Jr. *et al.*, Dordrecht: Kluwer, 769

Sekanina, Z. 1991b, AJ, 102, 1870

Sekanina, Z. 1991c, AJ, 102, 350

Sekanina, Z. 1993, in Activity of Distant Comets, W. F. Huebner *et al.*, San Antonio: Southwest Research Institute, 166

Sekanina, Z. 1995a, in The Collision of Comet P/Shoemaker–Levy 9 and Jupiter, K. S. Noll *et al.*, Cambridge, U.K: Cambridge University, in press

Sekanina, Z. 1995b, in European Shoemaker–Levy 9/Jupiter Workshop, R. West & H. Boehnhardt, Garching bei München: ESO, 29

Sekanina, Z., Chodas, P. W. & Yeomans, D. K. 1994, A&A, 289, 607

Sekanina, Z. & Farrell, J. A. 1980, AJ, 85, 1538

Sekanina, Z. & Farrell, J. A. 1982, AJ, 87, 1836

Sekanina, Z. & Farrell, J. A. 1986, BAAS, 18, 818

Sekanina, Z. & Larson, S. M. 1984, AJ, 89, 1408

Sekanina, Z. & Larson, S. M. 1986a, AJ, 92, 462

Sekanina, Z. & Larson, S. M. 1986b, Nature, 321, 357

Thomas, N. & Keller, H. U. 1987, A&A, 187, 843

Utterback, N. G. & Kissel, J. 1990, AJ, 100, 1315

Whipple, F. L. 1983, in Cometary Exploration I, T. I. Gombosi, Budapest: Hungarian Academy of Sciences, 95