Comet Shoemaker–Levy 9: an active comet

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Abstract. The important elements of the debate over the activity versus dormancy of comet Shoemaker–Levy 9 (S–L 9) are reviewed. It is argued that the circularity of the isophotes in the inner comae of S–L 9 as well as the spatial dependencies of the comae brightness profiles are indicators of sustained dust production by S–L 9. It is also shown that the westward tail orientations, which were formerly interpreted as a sign of the comet’s dormancy, are not a good indicator of either activity or dormancy. Rather, the tail orientations simply place constraints on the dust production rate for grains smaller than \( \approx 5 \mu m \). All the available evidence points to S–L 9 as having been an active, dust-producing comet. Synthetic images of an active comet are fitted to Hubble Space Telescope images of the S–L 9 fragment K, and its grain size and outflow velocity distributions are extracted. These findings show that the appearance of the dust coma was dominated by large grains having radii between \( \approx 30 \mu m \) and \( \approx 3 \, mm \), produced at a rate of \( M \approx 22 \, kg/s \), and ejected at outflow velocities of \( \approx 0.5 \, m/s \). Only upper limits on the production rates of smaller grains are obtained. The nucleus of fragment K was not observed directly but its size is restricted to lie within a rather narrow interval \( 0.4 \leq R_{\text{e}} \leq 1.2 \, km \). © 1997 Elsevier Science Ltd.

The activity of comet Shoemaker–Levy 9

Determining whether comet S–L 9 was active or dormant is necessary in order to successfully interpret the dust observations as well as to correctly infer the dusty-gas dynamical processes that may have occurred on its cometary surfaces. In fact, the distinction between activity versus dormancy alters the inferred mass of the S–L 9 dust grains by several orders of magnitude. According to the dormant-comet hypothesis, if most of the observed S–L 9 dust had been emitted by the comet fragments during the months just following the 1992 tidal breakup event and that S–L 9 had been relatively inactive ever since (e.g. Sekanina et al., 1994; Sekanina, 1996a), then one must conclude that the surviving coma grains observed one to two years later were large, having sizes exceeding about 1 cm. Initially, much smaller grains may once have been present but they had since been swept from the fragments’ coma by solar radiation pressure. However if the S–L 9 fragments were instead continuously emitting dust, then much smaller grains could have steadily replenished the coma as they continually drifted down the dust tails due to radiation pressure (e.g. Hahn et al., 1996).

Regardless of whether the comet fragments were active or dormant, there could not have been a large contribution to the observed coma optical depth by grains much smaller than a few microns (e.g. Sekanina et al., 1994; Hahn et al., 1996; Sekanina, 1996a). This fact may be inferred from the observed dust tails’ orientations. As cometary dust grains recede anti-sunward due to radiation pressure, keplerian shear causes the grains to drift in the direction opposite of the comet’s velocity vector. In heliocentric
The fragments when viewed either before or after solar opposition (see Fig. 1).

Comet S-L 9 was observed through two successive solar oppositions and no eastward dust features were detected (Sekanina et al., 1994; Chernova et al., 1996). Prior studies of S-L 9 often imply or conclude that the fragments were relatively dormant due to the absence of any eastward dust features (e.g. Sekanina et al., 1994; Chernova et al., 1996; Sekanina, 1996a). However this conclusion is premature since the observed dust tail orientations were consistent with both the active and the dormant comet hypotheses. The westward tail orientations observed after opposition instead provide an upper limit on the rate at which an S-L 9 fragment could have emitted grains smaller than a few microns, which is about 0.5 kg s⁻¹ as estimated by Sekanina (1996a) based on HST detection limits.

Frequently, cometary dust emission occurs from a few discrete spots on the surface a comet nucleus which, if rotating, can produce dust streams and spirals sometimes seen propagating through a dust coma. It should be noted that comet S-L 9 exhibited rather featureless dust comae which have also been interpreted as an indicator of the fragment's inactivity (e.g. Sekanina, 1996a). However, a featureless dust coma is not a strict indicator of inactivity, for it is also consistent with dust emission that was more evenly distributed across a fragment's sunlit surface. This is a reasonable possibility considering the S-L 9 fragments had effectively been stripped of any ancient surface mantle during the tidal disruption event which might otherwise have localized dust production to discrete spots.

There are, however, two lines of evidence that suggest S-L 9 had been actively replenishing its dust coma. The first is that contour maps of the light distribution in the fragments' innermost ≈ 1" comae regions remained quite circular throughout most of the comet's orbit (Weaver et al., 1994, 1995; Hahn et al., 1996; Rettig et al., 1996b). It has been noted that if S-L 9 had been dormant and its coma had consisted of large grains simply co-orbiting with the fragments, then the inner coma contours should have become progressively elongated along the fragment train axis as the fragment train itself lengthened with time (Weaver et al., 1995; Hahn et al., 1996; Weissman, 1996). In contrast, a comet that continuously replenishes its dust coma will maintain circular isophotes in its inner coma, as was exhibited by S-L 9 throughout most of its orbit.

A second line of evidence that favors activity is the coma surface brightness profiles. An idealized comet experiencing steady and isotropic dust emission will develop a dust coma having a column density varying as ρ⁻¹ with projected distance ρ from the coma photocenter. When the effects of radiation pressure acting upon a distribution of grains are considered, the brightness profile along the tail still varies as ρ⁻3/2 (generalizing the results of Wallace and Miller (1958)) whereas the azimuthally averaged brightness profile will develop a ρ⁻3/2 power law for sufficiently large ρ (Gewitt and Meech, 1987). Brightness profiles for fragment K, given in Fig. 2, clearly evidence such phenomena. All of the bright, on-axis frag-

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1 Except just prior to impact, the velocity of S-L 9 relative to Jupiter was small compared to the orbital velocity of the Jupiter-S-L 9 system about the Sun. Jupiter's gravity did not play a significant role in determining the appearance of the S-L 9 comae and tails until about a month before impact (Hahn et al., 1996).

2 The exception, of course, occurred during the month just prior to impact as the comae and tails become progressively elongated along the comet-Jupiter direction.
Simulations of an S-L 9 well as its dust phase law coefficient and an upper limit size and outflow velocity distributions are presented as the HST observations of fragment K. Fragment K's grain and a search of parameter space provides excellent fits to Jupiter. Synthetic images of model comae are constructed, simulations of an active comet in S-L 9's orbit about the Sun is the most likely source of the observed dust emission, although alternate theories exist (see Olson and Mead, 1965; Press et al., 1994). While only cursory comparisons of the appearance of dormant comet models to the observations have been made (Hahn et al., 1996), their ability to fully explain the observed S-L 9 phenomena are not promising. Below we describe Monte Carlo simulations of an active comet in S-L 9's orbit about Jupiter. Synthetic images of model comae are constructed, and a search of parameter space provides excellent fits to the HST observations of fragment K. Fragment K's grain size and outflow velocity distributions are presented as well as its dust phase law coefficient and an upper limit on the fragment's radius.

Simulations of an S-L 9 coma and tail

Synthetic images of cometary dust comae and tails have been computed for comet S-L 9. By fitting model images to the sequence of S-L 9 observations obtained with the HST throughout 1994, and minimizing the fit's χ², the comet's grain size and outflow velocity distributions are extracted. Only a brief description of the modeling efforts is described here; a detailed account of shall be provided in a future communication as well as results obtained from observations of several other S-L 9 fragments.

The motion of a model S-L 9 fragment is numerically integrated forward in time following the moment of tidal breakup. As it orbits Jupiter, the simulated comet fragment ejects dust grains of various radii R at velocity V(R) in random directions from its sunlit hemisphere. The model nucleus and its dust grains are subject to jovian and solar gravities with the grains also experiencing radiation pressure appropriate for their size. The model's dust size distribution is divided into nine discrete size bins ranging from R = 1 μm on up to 1 cm. The allowed ejection velocities V(R) are similarly discrete on 0.25 m s⁻¹ velocity intervals (this quantization of the problem makes it computationally tractable). If N(R,t) is defined as the cumulative number of all grains having radii smaller than R emitted by a given S-L 9 fragment up until some time t, then the task at hand is to solve for dN(R,t) = ARdN(R,t)/dR, which is the differential dust production rate of all grains in the size interval R±ΔR/2 at time t. The velocity distribution V(R) must also be solved for each size bin R. An important assumption made here is that the differential dust production rate dN(R) is constant with time. The comet dust is also assumed to obey the usual phase law log ψ(β) = −β/2.5, where β is the Sun–comet–Earth phase angle and the free parameter β is the phase coefficient. The additional light contributed by an unresolved spherical fragment of radius Rf is also included, and it is assumed to have a light distribution given by the HST point-spread-function. Thus 20 parameters specify a simulated set of S-L 9 observations—a dN(R), V(R) pair for each grain size bin plus β and Rf. Once a set of parameters are chosen, brightness maps of the coma and tail are computed for various observation dates.

The downhill simplex method is used to search the available parameter space and minimize the fit's χ² (Nelder and Mead, 1965; Press et al., 1994). A time-sequence of contour maps of fragment K observed with HST is given in Fig. 3 as well as the resulting isophotes of the fitted synthetic image. Although discrepancies exist between the observed and modal isophotes at faint light levels, there is overall good agreement between the observations and the fit. Figure 4 shows the fragment's dust production distribution dN(R) and its mass loss distribution dM(R) = (4π/3)ρgR³ dN(R) which assumes a dust geometric albedo of 0.04 and a grain mass density ρg = 1 g cm⁻³. The arrows represent upper limits on the production rates for the indicated size bins. These findings are typical of many comets in that production of the smallest grains are numerically favored but total mass loss rates are governed by the largest grains ejected. The mass

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1The fragment's ρ⁻¹ and ρ⁻³/² brightness profiles, as well as its nearly constant distance from Sun, suggest (but do not guarantee) that its dust production rate did not vary significantly during the span of observations considered here.
loss rate of grains detected in fragment K’s coma (30 \mu m \leq R \leq 3 mm) is $M \approx 22 \pm 5$ kg s$^{-1}$. Evidently, coma grains smaller than 30 \mu m did not contribute a detectable amount of light scattering cross section, so only upper limits on their production rates are obtained. It is noted here that the mass loss rate for grains smaller than 3 \mu m is at most 0.1 kg s$^{-1}$ and well below Sekanina’s earlier upper limit.

It is interesting to compare the grain size distribution for fragment K with that for comet Halley. As is evident in Fig. 4, a single power law cannot accurately represent the fragment’s grain size distribution. Nonetheless, computing the logarithm slope of $dN(R)$ over the 30 \mu m \leq R \leq 3 mm size interval indicates $dN(R) \propto R^{-3.7}$ with $a = 2.2 \pm 0.2$, which is considerably flatter than the $R^{-3.7}$ power law measured for comet Halley (Tokunaga et al., 1986; Waniak, 1992). If comet S–L 9 had produced small grains in the same proportions as comet Halley, then they would have been well above detection limits, as indicated by Fig. 4.

The uncertainties quoted in Fig. 4 are 68% confidence intervals in the model parameters where $\rho_R = 1$ g cm$^{-3}$ and $a = 0.04$ has been assumed. However our systematic uncertainties are affected by the unknown grain density and albedo. Radiation pressure sorts dust grains according to the product $\rho_R R$, so if the true S–L 9 grain density $\rho_R$ differs from the value assumed here then the $R$ axis in Figs 4 and 5 should be divided by a factor $\rho_R$ expressed in cgs units. The observed flux reflected by each grain size bin determines $aR^2 dN(R)$, so if an alternate albedo $a$ is also preferred, the grain production rates in Fig. 4 should be multiplied by $0.04\rho_R^2/a$. If $\rho_R$ is independent of grain size (which might not be true if smaller cometary grains are fluffy instead of compact) then it can be shown that the mass loss rates $dM(R) \propto \rho_R R^3 dN(R)$ are independent of the assumed grain density but still uncertain by a factor of $0.04/a$.

The dust outflow velocity distribution $V(R)$ for fragment K is given in Fig. 5 for the 30 \mu m \leq R \leq 3 mm grains, which, if described by a power law, would obey $V \propto R^a$.
with $b = 0.1 \pm 0.2$. The observed power-law dependence is significantly weaker than $b = 0.5$ predicted by the theory of dusty-gas emission from cometary surfaces (Gombosi et al., 1986) but this finding is typical of studies of other comets (Fulle, 1990, 1992, 1996; Waniak, 1992). The observed dust velocities, $0.5$ to $1$ m s$^{-1}$, are in good agreement with earlier estimates (Hahn et al., 1996a, 1996b), but they are significantly slower than the $0.4$ km or larger and would have ejected less than half its mass. Similarly, the smaller fragments F, J, P, P2, T, and U did not exhibit any impact signatures (Hammel et al., 1995; Chodas and Yeomans, 1996), so perhaps they simply exhausted most of their mass before they could strike the planet.

Conclusions

Since molecular fluorescence from any cometary gases were below detection limits, it is only from pre-impact observations of the dust that one might glean further insight into the structural properties of the tidally disrupted comet S-L9 fragments as well as the physics of their cometary atmospheres. For this reason it is critically important to correctly infer the history of dust emission by S-L9 and its grain sizes and outflow velocities. The photometry of S-L9 favors an active-comet hypothesis over dormancy, as evidenced by the circular isophotes in its inner coma and its $\rho^{-1}$ and $\rho^{-3/2}$ brightness profiles. Detailed comparisons of observations to an active-comet model further strengthens this contention.

The appearance of fragment K's coma and tail at visible wavelengths was governed by relatively large $30 \mu m \leq R \leq 3$ mm grains ejected at velocities $V \approx 0.5$ to $1.0$ m s$^{-1}$. Grains $10 \mu m$ and smaller were not detected above a one-$\sigma$ confidence level, but it is reasonable to assume they were produced at a rate below the $0.1$ kg s$^{-1}$ detection limit. The non-detection of small grains that are otherwise characteristic of most other comets is due to S-L9's rather flat size distribution, $dN(R) \propto R^{-2}$ to $R^{-0.6}$. One may speculate that its unusual size distribution was a consequence of the comet's tidally disrupted nature. Dust grains from most comets emanate from, and are perhaps filtered by, an
ancient overlying surface mantle. However a surface mantle is absent on a tidally disrupted comet, and this may have permitted the large S L 9 dust grains to escape with greater ease and result in a dust size distribution that was flatter than seen in most comets. The large grains seen in the S-L 9 coma may also be an indicator of the particular ices species that was responsible for the comet's dust emission. At S-L 9's distance from the Sun, water production would have been too feeble to launch any grains larger than \( \sim 1(1) \mu m \) from the surface of an \( R_S \approx 1(1) \) km comet fragment (see Hahn et al., 1996). However models indicate that the sublimation of more volatile species such as CO or CO2 may have been sufficiently vigorous to loft grains as large as a few millimeters.

During the 1994 observations, fragment K was ejecting the \( 30 \mu m \leq R \leq 3 \) mm grains at a rate of \( M = 22 \pm 5 \) kg s\(^{-1}\). In order to sustain this rather vigorous mass loss rate the radius of fragment K must have been \( R_K > 0.4 \) km at the time of breakup, while the dust coma modeling indicates that \( R_K < 1.2 \) km during the 1994 observations. Thus without ever observing fragment K directly, its radius is constrained to lie within a fairly narrow size interval.

A comparison of dust production by the S-L 9 fragment K to comets SW 1 and Chiron is in order; these bodies have estimated mass loss rates of \( \approx 600 \) and \( \approx 2 \) kg s\(^{-1}\), respectively (Fulle, 1992, 1994). However these comets are much larger than S-L 9, having radii \( R_{SW1} \approx 15 \) km (Altenhoff and Stumpff, 1995). A comparison of mass loss rates per nucleus surface area reveals that the surface of fragment K was at least \( \approx 6 \) times more active than S-W 1, and at least \( \approx 5 \times 10^3 \) times greater than Chiron. Thus this S-L 9 fragment, and perhaps all the others, were extremely active in comparison to other comets orbiting at comparable distances from the Sun. This fact may also be a consequence of S-L 9's tidal disruption which stripped any surface mantle from the fragments that might otherwise have constricted their dust production.

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