

# 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 here. 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  $\sim 5 \mu\text{m}$ . 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  $\sim 30 \mu\text{m}$  and  $\sim 3 \text{ mm}$ , produced at a rate of  $\dot{M} \sim 22 \text{ kg/sec}$ , and ejected at outflow velocities of  $\sim 0.5 \text{ m/sec}$ . 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  $0.4 \lesssim R_f \lesssim 1.2 \text{ km}$ .

Ever since the discovery of Comet Shoemaker–Levy 9 (S–L 9) in the spring of 1993 there has been an ongoing debate regarding its activity (Sekanina *et al.* 1994, Chernova *et al.* 1996, Hahn *et al.* 1996, Rettig *et al.* 1996b, Sekanina 1996a). This point is of no minor consequence, for in order to correctly understand the 1993–1994 observations of the S–L 9 dust comae and tails it is necessary to know whether one was viewing recent and possibly ongoing dust emission, or perhaps more ‘ancient’ dust emission that was triggered by the comet’s tidal breakup in July 1992. Arguments for and against the comet’s activity are described herein, and comparisons of observations of the S–L 9 fragment K to dust comae models will show that it was indeed an active, dust–producing comet. Estimates of its dust size distribution, mass loss rates, and dust outflow velocities are presented.

## 1. 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 comae 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’ comae 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 comae 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 comae 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 space, Comet S–L 9 was moving roughly eastward at approximately Jupiter’s orbital velocity,<sup>3</sup> so keplerian

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<sup>3</sup>Except just prior to impact, the velocity of S–L 9 relative to Jupiter was small compared to the orbital

shear was responsible for bending the dust tails west of the anti-solar direction. However the orientation of the tails projected onto an Earth–observer’s sky plane depended upon the degree of the tail’s curvature, and this was governed by the dust grains’ size. Smaller grains that were rapidly accelerating anti-sunward gave rise to straighter tails, whereas large and slowly-drifting grains contributed shorter tails having greater curvature. A schematic of the Sun–Comet–Earth viewing geometry for HST observations acquired in 1994 is sketched in Fig. 1. This diagram indicates that the dust tails should always have appeared west of the fragments when viewed prior to solar opposition. But after solar opposition, if there were detectable quantities of grains smaller than a critical size, the dust tails would have rotated  $180^\circ$  from west to east on the sky plane. The critical grain size is about  $5 \mu\text{m}$  for S–L 9 (Hahn *et al.* 1996). It is important to realize that grains larger than this threshold would have contributed tails that would always have appeared west of 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/sec as estimated by Sekanina (1996a) based on HST detection limits.

Frequently, cometary dust emission occurs from a few discrete spots on the surface of 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 fragments’ *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

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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).

replenishing its dust comae. The first is that contour maps of the light distribution in the fragments' innermost  $\sim 1''$  comae regions remained quite circular throughout most of the comet's orbit<sup>4</sup> (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 comae had consisted of large grains simply co-orbiting with the fragments, then the inner comae 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 comae 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 comae surface brightness profiles. An idealized comet experiencing steady and isotropic dust emission will develop a dust coma having a column density varying as  $\rho^{-1}$  with projected distance  $\rho$  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  $\rho^{-1}$  (generalizing the results of Wallace and Miller 1958) whereas the azimuthally averaged brightness profile will develop a  $\rho^{-3/2}$  power law for sufficiently large  $\rho$  (Jewitt and Meech 1987). Brightness profiles for fragment K, given in Fig. 2, clearly evidence such phenomena. All of the bright, on-axis fragments imaged with HST throughout 1994 have comae light distributions similar<sup>5</sup> to Fig. 2 (Hahn *et al.* 1996). It should be noted that brightness profiles extracted from the 1993 observations of S–L 9 differ distinctly from Fig. 2 and obey a  $\sim \rho^{-0.7}$  dependence (from Fig. 6 of Jewitt (1995), see also Weaver *et al.* 1994). This suggests that the S–L 9 dust production rate may have been decreasing with time prior to the 1994 observations considered here.

Spectroscopic searches for sublimating cometary gases have yielded null results for S–L 9 (Cochran *et al.* 1994, Weaver *et al.* 1994, 1995, Stüwe *et al.* 1995), which is not regarded as unusual for small icy bodies 5.4 AU away from the sun (Weissman 1996). An unobserved surface gas flow is the most likely source of the observed dust emission, although alternate theories exist (see Olson and Mumma 1994, Rettig *et al.* 1996a). 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

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<sup>4</sup>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.

<sup>5</sup>Again the exception is just before impact when Jupiter's gravity altered the coma/tail structures. Also, several of the dim, off-axis fragments did not exhibit profiles like those seen in Fig. 2

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.

## 2. Simulations of an S–L 9 Coma & Tail

Synthetic images of cometary dust comae and tails have been computed for Comet Shoemaker–Levy 9. By fitting model images to the sequence of S–L 9 observations obtained with the HST throughout 1994, and minimizing the fit’s  $\chi^2$ , the comet’s grain size and outflow velocity distributions are extracted. Only a brief description of the modeling efforts are 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 9 discrete size bins ranging from  $R = 1 \mu\text{m}$  on up to 1 cm. The allowed ejection velocities  $V(R)$  are similarly discrete on 0.25 m/sec 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  $\Delta R \times d\dot{N}(R, t)/dR \simeq d\dot{N}(R, t)$ , which is the differential dust production rate of all grains in the size interval  $R \pm \Delta R/2$  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  $d\dot{N}(R)$  is constant with time.<sup>6</sup> The comet dust is also assumed to obey the usual phase law  $\log \psi(\alpha) = -\alpha\beta/2.5$ , where  $\alpha$  is the Sun–Comet–Earth phase angle and the free parameter  $\beta$  is the phase coefficient. The additional light contributed by an unresolved spherical fragment of radius  $R_f$  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  $d\dot{N}(R), V(R)$  pair for each grain size bin plus  $\beta$  and  $R_f$ . Once a set of parameters are chosen, brightness maps of the coma and tail are

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<sup>6</sup>The fragment’s  $\sim \rho^{-1}$  and  $\sim \rho^{-3/2}$  brightness profiles, as well as its nearly constant distance from the Sun, suggest (but do not guarantee) that its dust production rate did not vary significantly during the span of observations considered here.

computed for various observation dates.

The downhill simplex method is used to search the available parameter space and minimize the fit's  $\chi^2$  (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 model 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  $d\dot{N}(R)$  and its mass loss distribution  $d\dot{M}(R) = \frac{4\pi}{3}\rho_g R^3 d\dot{N}(R)$  which assumes a dust geometric albedo of 0.04 and a grain mass density  $\rho_g = 1 \text{ gm/cm}^3$ . 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 loss rate of grains detected in fragment K's coma ( $30 \mu\text{m} \lesssim R \lesssim 3 \text{ mm}$ ) is  $\dot{M} \simeq 22 \pm 5 \text{ kg/sec}$ . Evidently, coma grains smaller than  $30 \mu\text{m}$  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  $3 \mu\text{m}$  is at most  $0.1 \text{ kg/sec}$  and well below Sekanina's earlier upper limit.

It is interesting to compare the grain size distribution for fragment K to 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  $d\dot{N}(R)$  over the  $30 \mu\text{m} \lesssim R \lesssim 3 \text{ mm}$  size interval indicates  $d\dot{N}(R) \propto R^{-a}$  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 Shoemaker–Levy 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 the Figures are 68% confidence intervals in the model parameters where  $\rho_g = 1 \text{ gm/cm}^3$  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  $\rho_g R$ , so if the true S–L 9 grain density  $\rho_g$  differs from the value assumed here then the  $R$  axis in Figs. 4–5 should be divided by a factor  $\rho_g$  expressed in cgs units. The observed flux reflected by each grain size bin determines  $aR^2 d\dot{N}(R)$ , so if an alternate albedo  $a$  is also preferred, the grain production rates in Fig. 4 should be multiplied by  $0.04\rho_g^2/a$ . If  $\rho_g$  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  $d\dot{M}(R) \propto \rho_g R^3 d\dot{N}(R)$  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  $30 \mu\text{m} \leq R \leq 3 \text{ mm}$  grains, which, if described by a power-law, would obey  $V \propto R^{-b}$  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; Waniak 1992, Fulle 1996). The observed dust velocities,  $\sim 0.5$  to  $1 \text{ m/sec}$ , are in good agreement with earlier estimates (Hahn *et al.* 1996, Rettig *et al.* 1996b), but they are significantly slower than the outflow velocities measured for large grains emitted by other distant comets:  $V \sim 15 \text{ m/sec}$  for Schwassmann–Wachmann 1 at 6 AU (Fulle 1992),  $V > 32 \text{ m/sec}$  for Hale–Bopp at 7 AU (Kidger *et al.* 1996),  $V \sim 5 \text{ m/sec}$  for Chiron at 9 AU (Fulle 1994), and  $V \sim 25 \text{ m/sec}$  for Hally at 14 AU (Sekanina *et al.* 1992). The low velocities observed in S–L 9 may indicate that its relatively large grains were poorly coupled to an unseen gas flow.

The parameter search algorithm yielded a phase law coefficient  $\beta = 0.010 \pm 0.006$  magnitudes/degree. However the fitting algorithm could not uniquely disentangle any light reflected by an embedded comet fragment from that contributed by the surrounding dust coma. Only an upper limit of  $R_f < 1.2 \text{ km}$  is obtained for fragment K’s radius assuming an  $a = 0.04$  albedo. This limit is about two times tighter than that reported by Weaver *et al.* 1995 and is slightly smaller than the size estimate given by Sekanina (1996b). Note that even smaller size limits/estimates have been obtained from models of the tidal disruption of the S–L 9 progenitor [ $R_f \sim \mathcal{O}(0.4) \text{ km}$ , Asphaug and Benz 1996], models of the Jupiter impact events [ $R_f \lesssim 0.5 \text{ km}$ , Mac-Low 1996], as well as the minimum impactor size that may be inferred from the amount of CO observed in Jupiter’s atmosphere at the K impact site [ $R_f \gtrsim \mathcal{O}(0.4) \text{ km}$ , Lellouch 1996], the source of which is thought to be of cometary origin.

The lower limit on the fragment’s radius is  $R_{\text{min}} = (3\dot{M}\Delta t/4\pi\rho_f)^{1/3} \sim 0.4 \text{ km}$  in order for a fragment of density  $\rho_f \sim 0.6 \text{ gm/cm}^3$  to sustain a dust production rate of  $\dot{M} \simeq 22 \text{ kg/sec}$  during the  $\Delta t \simeq 2 \text{ year}$  time interval between breakup and impact. Consequently, if it had an initial size smaller than  $0.4 \text{ km}$ , it would have completely evaporated before striking Jupiter. However, fragment K was indeed observed to strike Jupiter. Supposing this fragment maintained a constant dust production rate during its final orbit, then with an initial fragment radius of at least  $0.5 \text{ km}$ , the final impactor radius would have been  $0.4 \text{ km}$  or larger and would have ejected less than half its mass. Similarly, the smaller fragments F, J, P<sub>1</sub>, P<sub>2</sub>, T, and U did not exhibit any impact signatures (Hammel *et al.* 1995, Chodas and Yeomans 1996), so perhaps they simply exhausted most their mass before they could strike the planet.



### 3. 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 Shoemaker–Levy 9 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–L 9 and its grain sizes and outflow velocities. The photometry of S–L 9 favors an active-comet hypothesis over dormancy, as evidenced by the circular isophotes in its inner comae and its  $\sim \rho^{-1}$  and  $\sim \rho^{-3/2}$  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  $30 \mu\text{m} \lesssim R \lesssim 3 \text{ mm}$  grains ejected at velocities  $V \simeq 0.5$  to  $1.0$  m/sec. Grains  $10 \mu\text{m}$  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  $\sim 0.1$  kg/sec detection limit. The non-detection of small grains that are otherwise characteristic of most other comets is due to S–L 9’s rather flat size distribution,  $d\dot{N}(R) \propto R^{-2.2 \pm 0.2}$ . 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 comae may also be an indicator of the particular ice 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  $\sim \mathcal{O}(1) \mu\text{m}$  from the surface of an  $R_f \sim \mathcal{O}(1)$  km comet fragment (see Hahn *et. al.* 1996). However models indicate that the sublimation of more volatile species such as CO or CO<sub>2</sub> may have been sufficiently vigorous to loft grains as large as a few millimeters.

During the 1994 observations, fragment K was ejecting the  $30 \mu\text{m} \lesssim R \lesssim 3 \text{ mm}$  grains at a rate of  $\dot{M} = 22 \pm 5$  kg/sec. In order to sustain this rather vigorous mass loss rate the radius of fragment K must have been  $R_f > 0.4$  km at the time of breakup, while the dust coma modeling indicates that  $R_f < 1.2$  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 S–W 1 and Chiron is in order; these bodies have estimated mass loss rates of  $\sim 600$  kg/sec and  $\sim 20$  kg/sec, respectively (Fulle 1992, 1994). However these comets are much larger than S–L

9, having radii  $R_{\text{S-W 1}} \sim 15$  km (Meech *et al.* 1993) and  $R_{\text{Chiron}} \sim 84$  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  $\sim 6$  times more active than S-W 1, and at least  $\sim 5 \times 10^3$  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 have otherwise have constricted their dust production.

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Fig. 1. Lines of sight from Earth  $\oplus$  to S-L 9 are shown for selected HST observations acquired in 1994. A continuous stream of dust grains larger than about  $5 \mu\text{m}$  contribute curved tails that always appear west of the fragment, whereas smaller grains contribute straighter tails than appear east of the fragment when observed after solar opposition. Dust tails are not drawn to scale

Fig. 2. Sunward, tailward, and azimuthally averaged ( $360^\circ$ ) surface brightness profiles of fragment K on March 30, 1994. A  $\rho^{-1}$  curve is drawn over the tailward profile and a  $\rho^{-3/2}$  curve is plotted over the azimuthally averaged profile beyond  $\rho > 1''$ .

Fig. 3. Contour maps of fragment K (gray curves) and the fitted synthetic images (black curves). The coma observed on May 18 was clipped by the detector edge, and the ‘fins’ along the faint isophotes are an artifact of the model which ejects dust having discrete, rather than continuous sizes and velocities. A star trail lies north of the fragment on March 31, and the arrow in the June 27 figure indicates the projected direction to Jupiter.

Fig. 4. Fragment K’s differential dust production rate  $d\dot{N}(R)$  and mass production rate  $d\dot{M}(R)$  as a function of grain radius  $R$ . Arrows indicate upper limits. The dashed curve has the same logarithmic slope as an  $R^{-3.7}$  Halley-type grain size distribution.

Fig. 5. The dust outflow velocity for fragment K and an  $R^{-0.1}$  curve.

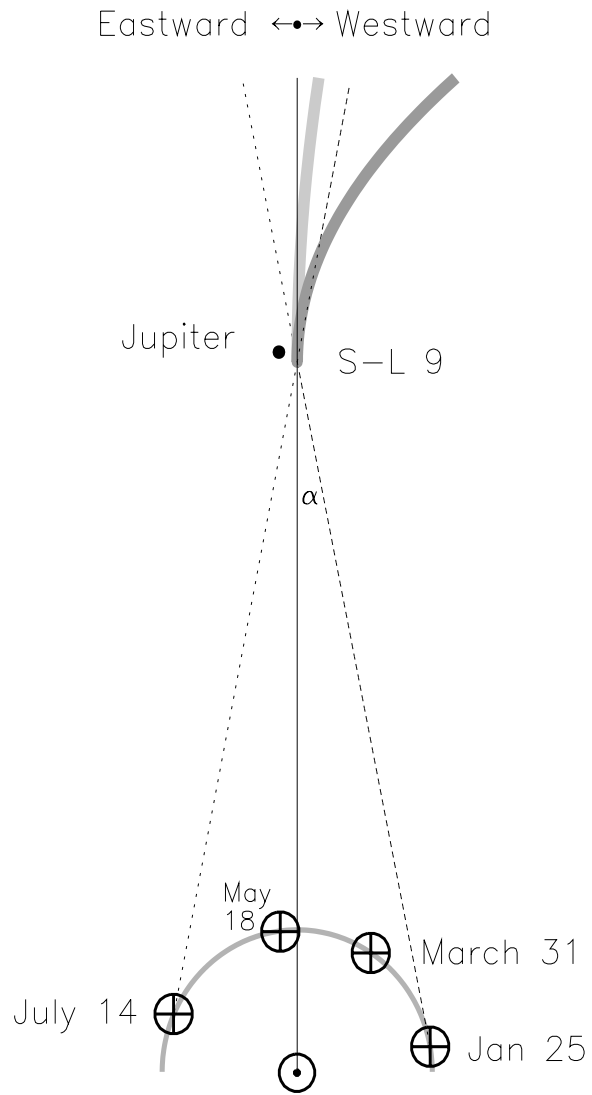


Fig. 1.—



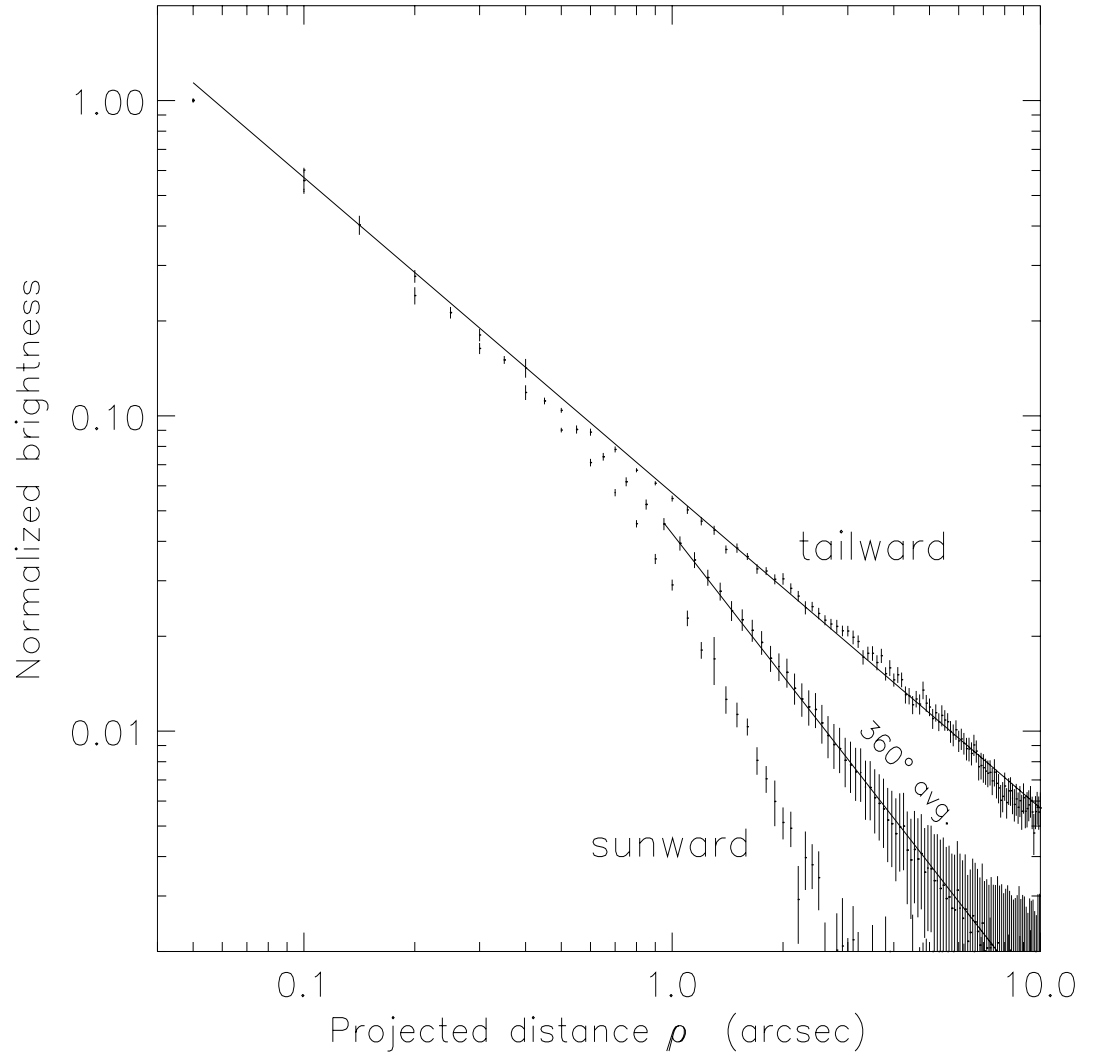


Fig. 2.—

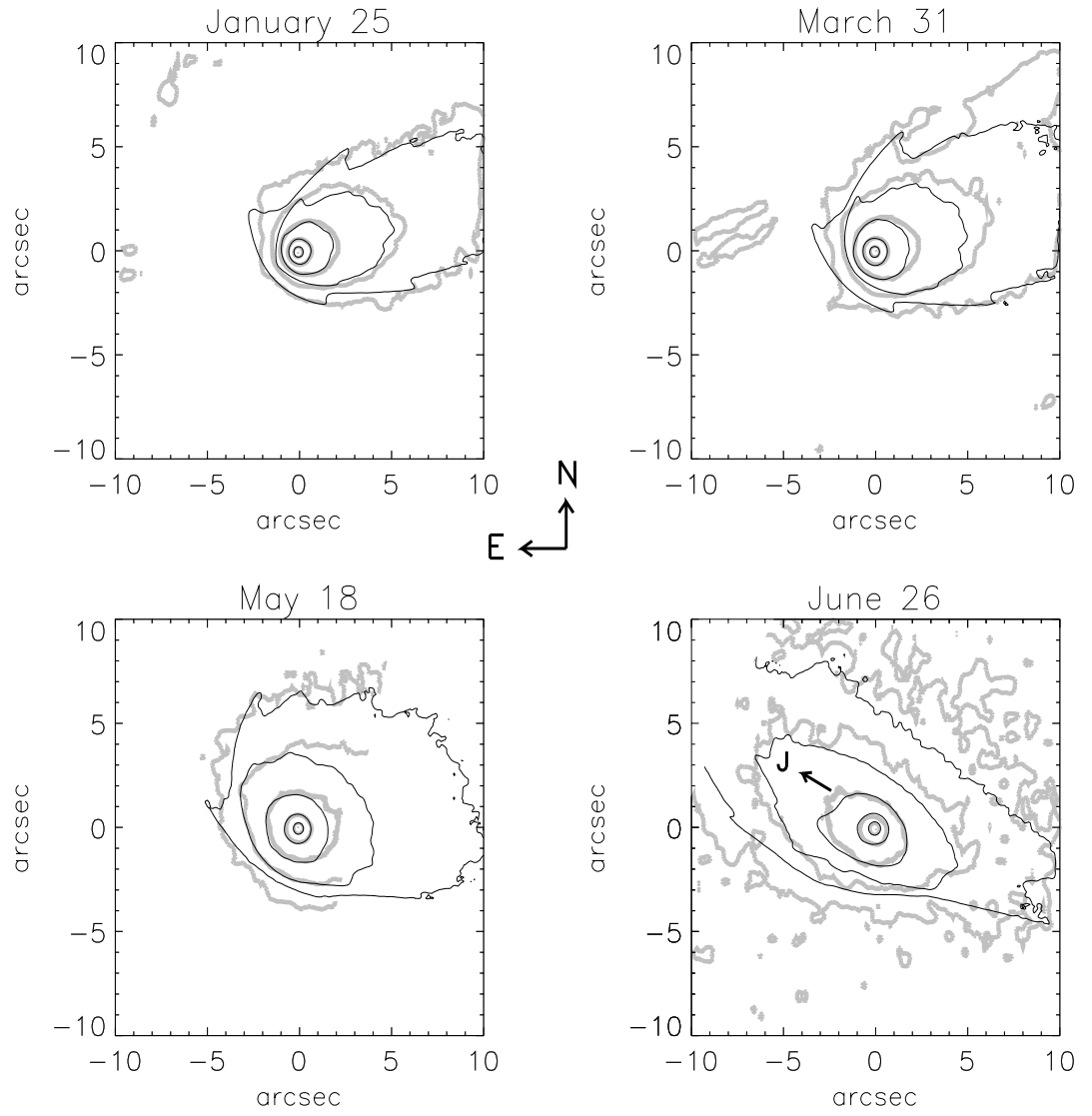


Fig. 3.—

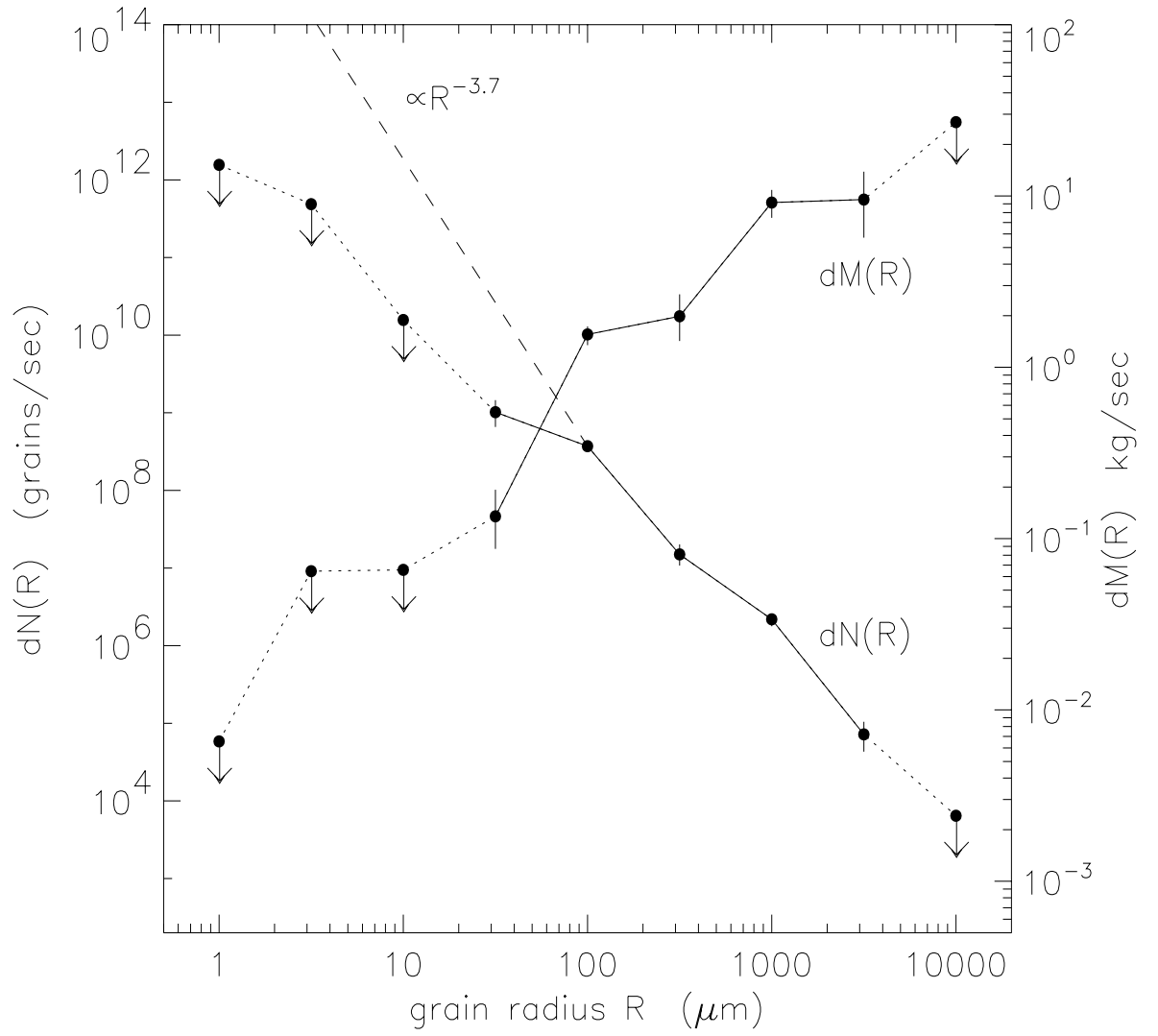


Fig. 4.—

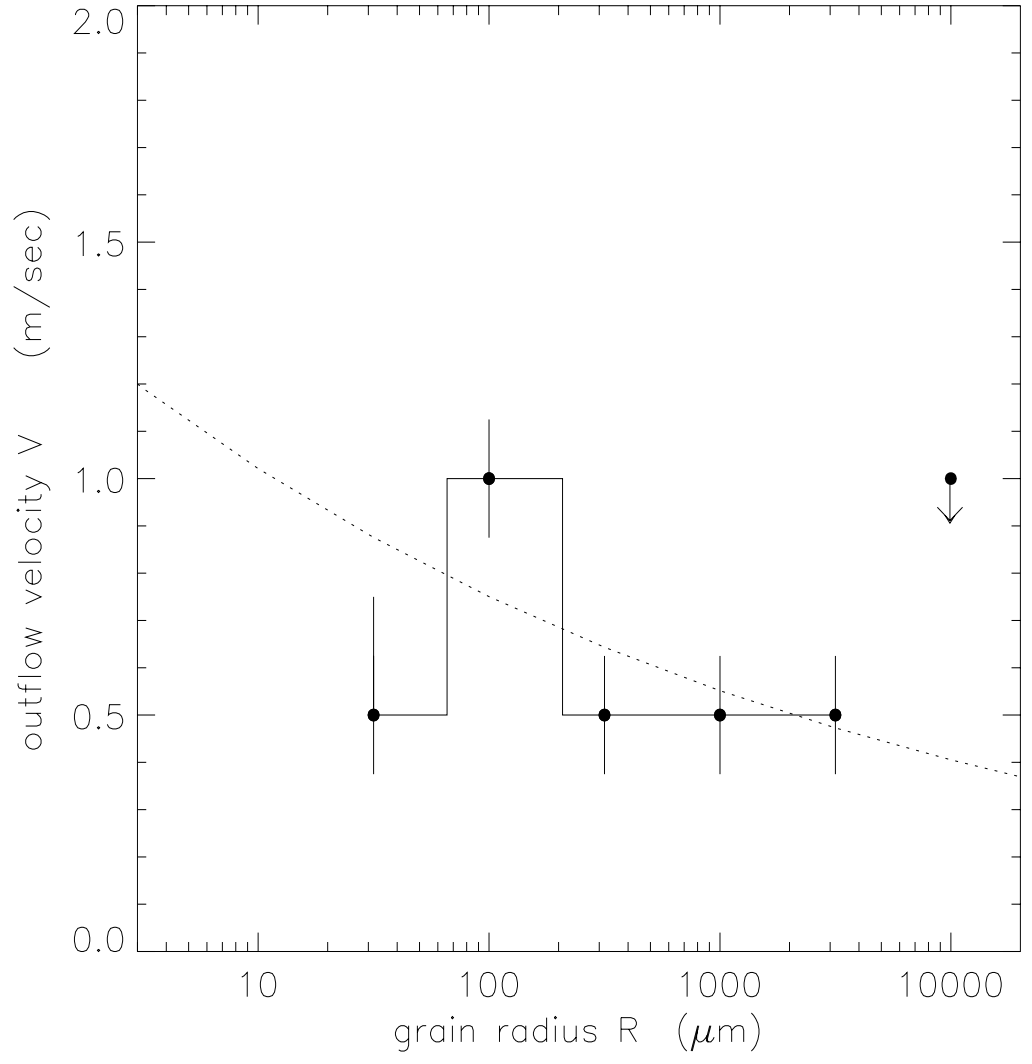


Fig. 5.—