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Fragmentation of Comet Shoemaker–Levy 9's Nuclei During Flight Through the Jovian Atmosphere

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Abstract. Fragmentation dominates the ablation process of cometary type impactors during their atmospheric flight. Models that account for it imply that a kilometer-sized nuclear fragment of comet Shoemaker–Levy 9 has disintegrated almost completely by the time of its terminal explosion, at a pressure level of <1 bar. This result, consistent with impact scenarios based on precursor-event timings, suggests that the initial masses of two fragments, K and R, were between 7×10^{14} and 5×10^{15} grams apiece.

Impact observations of the fragments K and R of comet Shoemaker–Levy 9 made, respectively, on July 19 and 21, 1994 from the ground and onboard the Galileo spacecraft are combined to constrain the penetration depths and the bulk properties of the impactors. The approach applied is based on slightly modified equations used in, and on ablation rates derived from, investigations of massive bolides in the Earth's atmosphere.

For "soft", cometary impactors these studies indicate that fragmentation—both continuous and occurring in discrete events that last $\leq$0.1 s—is the ablation process of paramount importance, vastly surpassing the effects of evaporation and spraying. The susceptibility to vigorous fragmentation is independent of the impactor's mass, with the necessary consequence of a *precipitous loss of mass during atmospheric flight*, an effect that has been neglected or grossly underestimated in most impact models for Shoemaker–Levy 9 proposed to date.

Meteor physicists have long been aware of the significance of fragmentation. Recently, its role was illustrated convincingly on the bolide Šumava (EN 041274) by Borovička & Spurný (1995), who showed that this morphological analogue to comet Shoemaker–Levy 9 and the most massive cometary bolide on record had an initial mass of ~5 tons, a bulk density 0.1 g/cm^3, and an effective ablation coefficient of 0.32 s^2/km^2. Its luminous trail began at 99 km above sea level, equivalent to ~380 km above 1 bar in the Jovian atmosphere, and the object disintegrated *entirely* at an altitude of 59 km, equivalent to ~190 km on Jupiter, at a dynamic pressure of ~1 bar and an atmospheric pressure of 0.25 mbar.

It is also known that large impactors explode instantly (e.g., McCrosky *et al* 1971, Sekanina 1983) at the terminal point of the luminous trajectory where the encountered atmospheric resistance can no longer be tolerated, i.e., at the point of peak dynamic pressure. In a simple model for a point source explosion, adapted to the case of an exponential atmosphere by Kompaneets (1960), a *strong* shock begins to propagate from the explosion point, with all the mass concentrated in a thin shell at its front (the shock regime). The pressure behind the front is proportional to the explosion's total energy and inversely to the expanding cavity's volume. The shock continues to expand at an accelerated rate upwards. The recondensed debris gradually trails behind (Boslough *et al.* 1994) and, because of Jupiter's gravity, it eventually follows a ballistic trajectory (the ballistic regime). The ejecta's maximum elevation was observed to be nearly independent of the explosion energy (Hammel *et al.* 1995), implying an equivalent "initial" upward velocity of ~13 km/s. Modelling this evolution constrains the time span between the explosion and the plume's emersion at the Jovian limb, the primary contributor to the observed timing of the precursor events, $t_\wedge - t_\vee$ (Figure 1). Similar conceptual models have independently been proposed by others (e.g., Boslough *et al.* 1995, Graham *et al.* 1995, Nicholson *et al.* 1995a).

The nominal scenarios for the nuclei K and R, listed in Table 1, are based on two assumed ablation coefficients, on the observed times $t_\wedge - t_\vee$ of 53 s for K (interpolated from the data by Watanabe *et al.* 1995) and 54 s for R (Graham *et al.* 1995), and on the effective initial diameters of 3.2 km for K (Sekanina, unpublished) and 2.4 km for R (Sekanina 1995), as determined photometrically from Hubble Space Telescope (HST) images. The impactors' initial masses are found to have ranged from 8×10^{14} to 5×10^{15} g, their bulk densities from 0.1 to 0.3 g/cm^3, and their residual masses from 2×10^{12} to 7×10^{12} g, or less than 1% of their preatmospheric masses. The explosion energies were near 10^{26} ergs and the explosion altitudes 40 to 60 km above 1 bar. The shock's downward penetration (Kompaneets 1960) should have extended for at least 30 km, thus affecting the NH_3 clouds. If the plumes were products of *line* sources (Boslough *et al.* 1994), the tabulated residual mass would be a lower limit to the plume's actual mass.

Table 1. Nominal ablation scenarios for fragments K and R

	Fragment K		Fragment R	
Ablation coefficient (s^2/km^2):	0.2	0.4	0.2	0.4
IMPACTOR AT TIME OF ATMOSPHERIC ENTRY				
Preatmospheric mass (g)	$10^{15.27}$	$10^{15.69}$	$10^{14.88}$	$10^{15.34}$
Kinetic energy (erg)[a]	$10^{28.51}$	$10^{28.93}$	$10^{28.12}$	$10^{28.58}$
Bulk density (g/cm^3)	0.11	0.29	0.10	0.30
Effective diameter (km)	3.2	3.2	2.4	2.4
IMPACTOR AT TIME OF TERMINAL EXPLOSION				
Residual mass (g)	$10^{12.74}$	$10^{12.86}$	$10^{12.34}$	$10^{12.50}$
Residual energy (erg)	$10^{25.98}$	$10^{26.10}$	$10^{25.58}$	$10^{25.74}$
Residual effective diameter (km)	0.46	0.36	0.34	0.27
Altitude above 1 bar (km)	50	44	57	49
Ambient atmospheric pressure (bar)	0.080	0.11	0.058	0.085
Aerodynamic pressure (bar)	562	795	383	600
Preatmospheric-to-residual mass ratio	340	680	350	700
TIME LINE OF EVENTS BEHIND JOVIAN LIMB[b]				
Impactor's flight from disappearance to explosion (s)	7.9	8.0	4.4	4.5
Plume's expansion in shock regime (s)	38.0	37.2	49.6	49.5
Plume's expansion in ballistic regime (s)	7.1	7.8	0.0	0.0
Total time behind Jovian limb[c] (s)	53.0	53.0	54.0	54.0

[a] Assuming that impactor's velocity coincided with velocity of escape at altitude of 1000 km above 1 bar.

[b] Assuming an isobar of 100 mb (Chodas 1995): 390 km (fragment K) and 245 km (fragment R) for altitude of impactor's disappearance and 340 km (K) and 210 km (R) for altitude of plume's appearance.

[c] Fitting observed interval between peak of first precursor and onset of second precursor; for fragment K the two times were interpolated to be 10:24:09 and 10:25:02 UT on July 19, 1994 from the data by Watanabe *et al.* (1995); for fragment R they were taken from Graham *et al.* (1995).

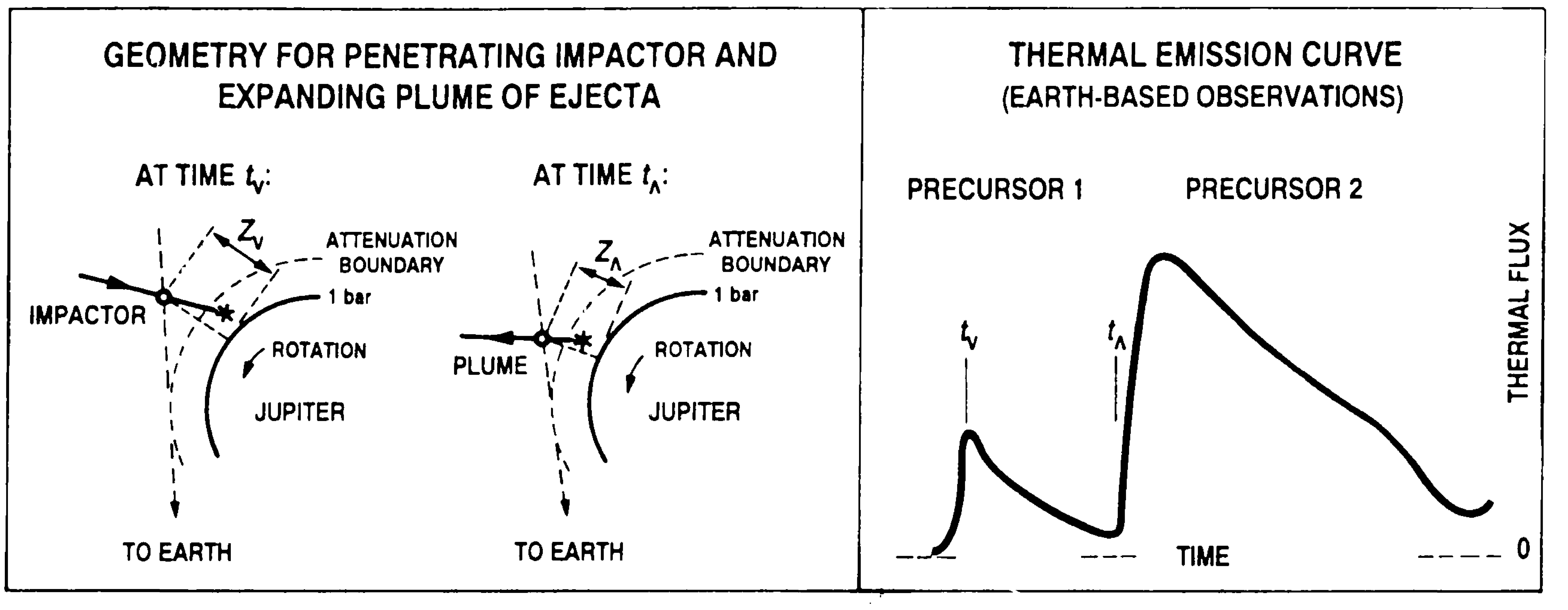

Figure 1. Geometry for a massive impactor penetrating the Jovian atmosphere and for an expanding plume of hypervelocity ejecta (left panel); and the pre-main event portion of the thermal emission curve as observed from the ground (right panel). The flux increases until the impactor disappears behind the limb at altitude Z_V at time t_V, when Precursor 1 reaches its peak. The signal then subsides, being due to the wake of ablated material and a trailing column of the disturbed atmosphere. The terminal explosion of the impactor's residual mass is hidden behind the limb. The sudden onset of Precursor 2, at time t_Λ, coincides with the front of the expanding ejecta's plume as it emerges over the limb at altitude Z_Λ. The difference $t_\Lambda - t_V$, the total time of the events occurring behind the limb, is the impact's key parameter.

The results in Table 1 are consistent with the timing of relevant events from experiments carried out onboard the Galileo spacecraft. The explosion time for K, 10:24:17 UT, coincides with the sharp peak on the light curve (Chapman *et al.* 1995) to 1 s, whereas for R the explosion time, 05:34:57 UT, differs from Carlson *et al.*'s (1995) reference time by 11 s, within their errors of measurement.

The 2.3 μm fluxes reported for Precursors 1 by Watanabe *et al.* (1995) for K and by Graham *et al.* (1995) for R were used to derive the impactors' effective surface areas, $S_{\rm eff}$, in units of their initial frontal areas A_0, and the product of a heat transfer coefficient $\Lambda < 1$ and a fraction $\chi < 1$ of the total energy spent on thermal reradiation as functions of temperature. The results, in Table 2, show that the signal from R at 530 km constrains the effective temperature at that altitude to $\leq$1000 K. Higher temperatures could, however, apply at the two lower altitudes. Nicholson *et al.* (1995b) found a color temperature of 1000 K. In the Earth's atmosphere, the surface temperature range for a 60 km/s projectile at equivalent altitudes has been estimated at $\sim$1500 to $\sim$3000 K (Bronshten 1983).

The possibility of a complete or nearly complete disintegration of impactors before their terminal explosion, predicted from the present model, is consistent with the reported failure, by a number of observers, to detect the ejecta plumes for virtually all of the off-train fragments, such as B, F, P_2, or V. Since the residual mass of each impactor depends on its initial mass, velocity, and ablation (fragmentation) rate, it is apparent that the off-train nuclei were both smaller and less cohesive than the on-train nuclei, fragmenting almost spontaneously.

Table 2. Effective temperature $T_{\rm eff}$, effective emitting area $S_{\rm eff}$ (in units of impactor's preatmospheric frontal area A_0), and a product $\dot{\chi}\Lambda$ from observed thermal fluxes for Precursors 1 of fragments R and K

Effective temperature $T_{\rm eff}$ (K)	Fragment R at altitude of 245 km		Fragment R at altitude of 530 km		Fragment K at altitude of 390 km	
	$S_{\rm eff}/A_0$	$\chi\Lambda$	$S_{\rm eff}/A_0$	$\chi\Lambda$	$S_{\rm eff}/A_0$	$\chi\Lambda$
2610	1.0	0.0053	..	..	...	...
2385	1.3	0.0037	...	...	1.0	0.55
2000	2.1	0.0018	...	...	1.7	0.27
1600	4.8	0.00075	...	...	3.7	0.11
1300	12	0.00033	...	...	9.1	0.049
1000	51	0.00011	30	0.65	38	0.017
800	240	0.00005	140	0.26	180	0.007
700	750	0.00003	440	0.15	520	0.004

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References

Borovička, J. & Spurný, P. 1995, Icarus, submitted

Boslough, M. B., Crawford, D. A., Robinson, A. C. & Trucano, T. G. 1994, GRL, 21, 1555

Boslough, M. B., Crawford, D. A., Trucano, T. G. & Robinson, A. C. 1995, GRL, 22, 1821

Bronshten, V. A. 1983, Physics of Meteoric Phenomena. Dordrecht: Reidel, 52

Carlson, R. W. *et al.* 1995, GRL, 22, 1557

Chapman, C. R. *et al.* 1995, GRL, 22, 1561

Chodas, P. W. 1995, personal communication

Graham, J. R., de Pater, I., Jernigan, J. G., Liu, M. C. & Brown, M. E. 1995, Science, 267, 1320

Hammel, H. B. *et al.* 1995, Science, 267, 1288

Kompaneets, A. S. 1960, Sov. Phys. Dokl., 5, 46

McCrosky, R. E., Posen, A., Schwartz, G. & Shao, C.-Y. 1971, JGR, 76, 4090

Nicholson, P. D. *et al.* 1995a, GRL, 22, 1613

Nicholson, P. D. *et al.* 1995b, GRL, 22, 1617

Sekanina, Z. 1983, AJ, 88, 1382; errata: AJ, 89, 185

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

Watanabe, J.-i. *et al.* 1995, PASJ, 47, L21