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PREDICTIONS WITH SATELLITE
OBSERVATIONS**

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COMPARISON OF FILTER PREDICTIONS WITH SATELLITE OBSERVATIONS

Gregory H. Canavan

Satellite observations of meteor entry are used to calibrate a filter model of fragmentation. Predicted sizes and masses compare favorably with data and analytic interpretations for objects of all sizes. However, objects that fragment into many large objects should be treated by the decomposition of the radiation signal into the contributions from the different fragments.

Introduction. Earlier notes derived a model for the hydrodynamics, ablation, and radiation of meteor impacts at the level needed to infer meteor parameters from observations and extended it to objects that fragment during entry using models based on cometary studies, resulting in a simple filter for the estimation of the parameters of entering objects.¹ A companion note² compared the predictions of the filter model to European and Prairie Network (EN and PN) data and models of meteor impact, for which US and other models gave broadly consistent agreement with each other and the data.

This note extends that comparison to the satellite network (SN) observations. The quantitative analysis of the SN data is discussed in conjunction with that of the Russian program of SN data analysis, which has bypassed the reported photometrically based masses to derive estimates of sizes, masses, and radiation efficiencies, which are the primary quantities of concern for this comparison. This note completes the discussion of the SN data, uses it to produce filter predictions, and compares them with SN observations and Russian analytic predictions. Their overall agreement is useful in that the Russian efforts have employed more complex models that use observational data directly, while the filter model is at a level of simplification better suited to data inversion.

The note reviews the filter model and exhibits and discusses its main scaling relationships. It uses criteria defined by PN, EN, SN, and Russian efforts to identify likely breakup candidates, reviews the released SN data base, extracts scaling relationships, discusses each SN object for which light curves are available, and reviews in depth the 19 objects for which satellite light curves are released. The seven objects for which trajectory information, radiation altitude, and Russian analyses are available are given detailed analysis, including numerical calculations. The correlation of sizes is good for objects up to about 3 m; for larger inferred masses, filter masses are lower.

A few objects are difficult to analyze because their power is modeled well by inferred parameters, but the total radiated energy is not. It appears necessary to account for the distinct peaks, and tail, of the light curve to achieve quantitative agreement. However, the filter works well without adjustment for both the largest objects and the smallest and also for light curves

with multiple humps, although the additional structure can degrade estimates of intermediate parameters.

In the interpretation of the signatures of unknown objects, filters would appear to have two types of limitations: information and decomposition. The former is due to the need for an estimate of the radiation altitude, and the latter is due to the need to, at a minimum, use the ratio of the overall pulse width to that of a single fragment as an estimate of the number of fragments in estimating power and radiated energy. However, SN observations, like PN and EN data analyzed earlier, have been shown to provide a useful test of the filter model, a positive assessment of its fidelity, and a good basis for its comparison with other analyses.

Review of filter model. The filter model is based on the observation that after an object fragments due to dynamic pressure, its area rapidly expands to a size such that drag causes it to decelerate abruptly, radiating strongly in the process. Each of these steps can be treated analytically. Since SN primarily provides information on the maximum radiated power $P_{\max}$, duration $t_{\max}$, and fragmentation altitude Z , they are the relevant variables for analysis. The relationships between them were derived earlier are³

$$t_{\max} \approx 0.7b^{1/3}q^{4/3}D/kV_0, \quad (1)$$

$$V_0 \approx 0.7b^{1/3}q^{4/3}D/kt_{\max}, \quad (2)$$

$$P_{\max} \approx 0.2f(0.7b^{1/3}q^{4/3}Dk/t_{\max})^3\rho_a D^2/q^{4/3}, \quad (3)$$

$$D \approx [17k^3t_{\max}^3P_{\max}/f\rho_a q^{8/3}b^{5/3}]^{1/5}, \quad (4)$$

where D is the object diameter, V_0 is its initial velocity, ρ_a its density, f its radiation efficiency, q is a function of density ratios $q(Z) = \sqrt{[\rho_a/\rho(Z)]}$, and $b = 3k/2NC$ where $k \approx 0.7$ is the coefficient in the fragment expansion velocity $v \approx k\sqrt{(\rho/\rho_a)}V_0 = k\sqrt{(\rho/\rho_a)}V_0/q$, $C \approx 1$ is the drag coefficient, and $N \approx 1$ is a parameter from the filter averaging. Thus, $b \approx 1$ for nominal parameters. D scales strongly on $t_{\max}^{3/5}$; less strongly on $P_{\max}^{1/5}$.

Review of SN data taken from distant satellites. Observations are primarily in the visible with fast time resolution, although there are also some observations in the infrared with few tenth second resolution. They do not generally determine the object velocity or the altitude of fragmentation or maximum radiation. Most observations have been released in the form of peak power, radiated energy, and inferred kinetic energy and radiating efficiency, as shown in Table I, which gives the aggregate data on bolides released through July 1996.

Figure 1 plots radiated energy versus peak power, which shows that above ~ 30 GW/sr or 0.03 kT, the two are essentially proportional with a relationship $Er(kT) \sim P(\text{GW/sr})/1000$. This scaling holds over almost three orders of magnitude in power and energy, including the region containing most of the large impactors of interest.

Figure 2 shows the relationship between inferred D and radiation efficiency f . The relationship is roughly linear up to $D \sim 1$ m, after which it increases more slowly, reaching ~ 0.1

by 4 m and 0.13 by 5 m. The inferred diameter is determined by assuming that the velocity and density are the same for all of the objects in Table I and estimating D by equating $(\rho_a D^3/2)V^2/2$ to the inferred kinetic energy $= E_r/f$. With the same approximation, Table II shows the inferred diameters for objects with released light curves predicted by the filter equations above. These diameters are also plotted in Fig. 3, which shows a strong correlation between the diameters inferred from kinetic energy and those filtered from the observed peak power. This agreement does not just reflect commonality of assumptions as the filter equations are insensitive to object velocity and density, which are the principal uncertainties in the kinetic inference.

Figure 4 shows the ratio of D to the radiation pulse width, as defined by the ratio of the radiated energy to the peak radiation rate. While there is considerable scatter in the data, it does appear that the points for $t > 0.1$ s fall along a line with $D \sim t$, with the top points having $D/t \sim 10$ m/s, which reflects a clear correlation between size and pulse length.

Light curves observed by satellites have been released for the 19 objects shown on Table II. As these light curves provide considerable additional insight into the phenomena taking place during their entry, they are reviewed briefly below.

88106. Figure 5 shows that PN 88106 had four peaks of increasing amplitudes, each about 0.5-0.1 s in duration. This succession of peaks resembles the succession of fragment decelerations seen in EN 70591 Benesov and EN 41274 Sumova, suggesting the possibility of a decomposition in terms of individual fragment power functions.⁴ The highest peak is about 900 GW/sr, after which the curve shows a smooth decay that lasts almost a second, which does not come out of fragmentation models.

90274 has a peak of about 300 GW/sr, a width of ~ 0.5 s, and a 0.5 s precursor foot at the $\sim 10\%$ level. The curve increases to its peak in ~ 0.1 s and then has several humps about 0.3s / 0.1s ~ 3 fragments wide. Its altitude is known to be ~ 30 km from "companion locators," which makes it particularly valuable for code calibration. Academician Nemtchinov has noted the analogy to 94307, but observed that the fragmentations at 15 and 3 bar imply low strength and density. It has many fragments, like the Sikhote-Alin fall, so it may have fragmented early.⁵

91277 has two obvious pulses each about 0.3 s wide and 30-50 GW/sr high. Otherwise, it has little structure. The curve could represent an object at low velocity or oblique incidence. Academician Nemtchinov noted the similarity to 94149, but also the quite different durations of their light pulses.

93304 seems to have two peaks, each about 0.2 s wide. However, the curve is noisy with $S/N \sim 2$, so it is hard to tell. Nemtchinov has observed that there is "no evidence of gross-fragmentation, as the growth rate is rather low."

93333 has three roughly equal peaks, each about 0.1 s in duration and about 10 GW/sr high, which could represent three separate fragments. The curve also has a long decay tail.

94032 is large, bright object with a main peak about 0.5 s and 3,000 GW/sr. It also has a pronounced ~ 0.7 s foot at ~ 400 GW/sr. It left debris at 34 and 21 km, although there is significant discrepancy over energy, mass, and radiation efficiency.

94149 has a clean 0.1 s, 100 GW/sr peak, which suggests a high velocity or vertical incidence, and a 0.5 s tail. Prof. Svetsov of the Nemtchinov group used velocity parameters of $0.5 < k < 1$ to successfully model the results; however, the resulting velocities are just bounds. Academician Nemtchinov argues that the fact that the bounds are wide is due to “the fact that the signal at the bolide (pre-breakdown) stage of the flight is rather noisy;” however, most of the signal is actually very clean. The assumption of higher velocity requires the assumption of greater strength as well.

94154 appears to have three separate ~ 100 GW/sr pulses, the first two separated by ~ 0.2 s and the third by 0.1 s. The first peak is ~ 0.1 s wide; the second two are each < 0.1 s. This also seems to be a useful candidate for decomposition.

94166 has $S/N \sim 2$ and a drifting baseline, but seems to contain a single 5 GW/sr peak with a rise time ~ 0.1 s.

94227 has two separate 30 GW/sr peaks separated by about 0.5 s. Academician Nemtchinov has argued that the “two light curves demonstrate that there are probably two independent impacts with very similar masses and energies divided by a very short time interval of about 0.5 s.” However, that explanation is somewhat improbable, as it would require a separation of $0.5 \text{ s} \times 30 \text{ km/s} = 15 \text{ km}$, which would be difficult to maintain before entry or generate during it. An alternative explanation is that two fragments separated early in entry and fragmented at different altitudes due to their different strengths, the weaker fragmenting $\sim 15 \text{ km}$ higher. The second peak actually seems to contain two objects about 0.1 s wide.

94293 has two separate flashes. The first is a 0.5 s, 5 GW/sr foot. The second has a ~ 0.1 s rise to 14 GW/sr, then a slow decay. The long foot suggest multiple breakups at high altitude. Academician Nemtchinov has also argued that “the first one is caused by the breakup at much higher altitude than for the second one.”

94300 has a 0.8 s ramp buildup, then two ~ 80 GW/sr spikes about 0.1 s in duration. There are also two more ~ 30 GW/sr spikes during the ramp and the tail.

94307 has a 0.5 s large foot, a 170 GW/sr spike, and then a ~ 0.2 s plateau containing 2-3 peaks. The debris reached 12 km, which is difficult to model. Academician Nemtchinov has argued that this object is analogous to 90274, except that the rise of radiation is faster than that of the density. He concludes that “probably the rate of the cloud expansion and the maximum radius of the cloud are rather close...” He finds the slow decay rated for this and other objects “astonishing.”

94347 has a single noisy 12 GW/sr peak 0.1 s wide plus another peak during decay.

94350 has a main 30 GW/sr peak and two more half that size during rise and decay. Each is about 0.05 s. Svetsov used $0.5 < k < 1$ to model the entry.

95004 has one peak ~ 0.5 s wide and another ~ 0.2 s. Both have ~ 0.1 s rise and 15 GW/sr peaks. The first plateau could contain 3-4 individual peaks. The second is apparently single.

Comparisons. The objects shown on Table III are a useful subset of the SN observations for which the height of maximum radiation is known with some precision through “companion locators.” The radiated energies and peak power are largely taken from the preceding figures. The ARD (air radiation dominated) and AP (ablative piston) models are those used by the Russian analysts to infer the parameters shown, which closely resemble those used for the detailed numerical calculations used to support comparisons below. The parameters produced by variation of parameters to produce best agreement with observables include radiation efficiency, kinetic energy, mass, velocity, and probable composition.

With this information it is possible to use Eqs. (1)-(4) to predict object diameter, mass, velocity, and composition, which are shown in Table IV. For objects 88106 and 91277 there are only single estimates. For the others, there are two estimates corresponding to the extreme parameter values given in Table III. Filter derived diameters are plotted against the inferred Russian diameters in Fig. 21. The diagonal line would indicate perfect correlation between them; the distance of a pair wise point from the line is a measurement of the degree of their de-correlation. The two models agree well to diameters of about 3 m. For larger objects, the filter predicts smaller diameters, with the discrepancy increasing when the larger of the values in Table III are used—largely due to the strong sensitivity of the inferred values. Figure 22 shows the correlation of velocities. The overall agreement is adequate, given the range of values in Table III, but the prediction of 70 km/s for object 88106, for which the Russian analysis predicts 45 km/s, deserves attention.

88106 shows the greatest discrepancy between filter and inferred parameters for of any of the objects. It is large and fast and produced its peak radiation at an unusually high altitude or 43 km. Figures 23 and 24 show power versus time (P vs t) and power versus altitude (P vs z) from a detailed numerical calculation using the inferred parameters of Table III: 25 tons, 45 km/s, and a radiation efficiency $f = 19\%$. To achieve fragmentation at 70 km and deposition at 43 km it was necessary to use a strength of 1 bar, which is low for a stony object.

Figure 24 shows that the power grows exponentially after fragmentation at 70 km to its peak at 43 km, after which it falls very rapidly. Figure 23 shows that power also grows rapidly with time until 0.5 s after fragmentation, when it reaches about 750 GW/sr, which is some what less than the 900 GW/sr of Fig. 5 and significantly less than the (inconsistent) 1,400 GW/sr of Table III. However, this is a fairly coarsely zoned calculation; the discrepancy decreases with finer step sizes.

A greater concern is the radiated energy. The numerical calculation integrates to 0.25 kT, while the value given by Table III is 1.7 kT. A factor of two of the difference can be accounted for by peak power, but that leaves about a factor of four. The reason for it is suggested by Fig. 23, which shows that the width of the computed power pulse is about $0.52 - 0.42 = 0.1$ s, which is only about a quarter of the full width shown in Fig. 5. To oversimplify, the tail, which is not accounted for in the numerical calculations, contributes about 20-30% of the total energy, and the precursor foot contributes another 10-20%. That leaves 50-70% from the three peaks, so that each should contribute about $0.5 - 0.7 \times 1.7 \text{ kT} / 3 \approx 0.3 - 0.4 \text{ kT}$, which is the order of the adjusted contribution from Fig. 23.

This argument implies that in order to obtain quantitative agreement on badly fragmented objects, it will be necessary to account for the fragments individually. However, it also indicates that the main information needed to estimate their number is the ratio of the observed pulse width to that of a predicted individual fragment, which is calculable.

90274 has a long foot and tail and a wide, high peak. Although it is one of the largest objects, Fig. 21 shows that the filter size agrees with the inferred value quite well for all parameter values for a strength of 10 bars. Figure 25 shows P vs t which has a peak of 500 GW/sr and width of $\sim 1.2 - 0.8 \sim 0.4$ s, in agreement with Fig. 6. The radiated energy is 0.6 kT, which is in agreement with the 0.57 kT of Table III. Figure 26 shows that the fall in the radiation after peak is not as sharp for this object, which is large, but relatively simple to calculate.

91277 has a large, double-humped light curve. Figure 21 shows that the filter model agrees well with the inference of its size. Figure 27 shows P vs t , which peaks at 120 GW/sr with a width of 0.4 s. This width is about twice that of Fig. 7, but the peak power is about twice that observed; thus, the computed radiated power of 0.13 kT agrees well with the observed value. A simple explanation is that each of the humps represent a separate fragment. Thus, dividing the mass in half, which would roughly halve the power in each, and assuming non-overlapping deposition times would essentially reproduce the curve in Fig. 7.

94032 has a long foot and tail and a 0.1-0.2 s 3,000 GW/sr peak. Figure 21 shows that the filter agrees well with the inferred diameter for the foot (part A); less so for the main body (part B). Figure 28 shows P vs t , which has a 4,000 GW/sr peak ~ 0.4 s in width, which is in agreement with part B on Fig. 10. The radiated energy is 3 kT, in reasonable accord with the 4.4 kT of Table III.

94149 is a clean 0.1 s, 100 GW/sr spike with a long tail. Figure 29 shows the numerical P vs t , which has a peak of 70 GW/sr and a width of ~ 0.1 s, which matches the observations. The radiated energy is 0.025 kT, which is lower than the value in Table III. Part is due to the peak value; the rest is apparently due to the long tail.

94307 has a large foot, multiple spikes, and a 300 GW/sr plateau. Figure 30 shows the numerical P vs t , which has a peak of 450 GW/sr and a width of ~ 0.35 s, in agreement with the broad plateau. The radiated energy of 0.5 kT agrees with the 0.56 kT of Table III. Thus, it appears possible to separate out the foot for calculations, although Fig. 21 shows that degrades the estimate of the object size.

94350 is a small and noisy, but it has a sharp curve with three clear spikes. Figure 21 shows that the filter agrees well with the inferred diameter. Figure 31 shows P vs t , which reaches 40 GW/sr for 0.06 s, in agreement with Fig. 19. The radiated energy is 0.007 kT, which is in reasonable agreement with the 0.0086 kT of Table III. This indicates that the filter works well for the smallest objects as well as the largest.

Summary and conclusions. This note extends the test of the filter model to comparisons with observations from the satellite network and with supporting inferences by the Russian analytic effort, which has produced more plausible estimates of the sizes, masses, and radiation efficiencies that are the primary quantities of concern for this comparison. This note uses SN data to produce filter predictions of size, mass, speed, and duration and compares them with other SN observations and the predictions of the Russian efforts. The general agreement is useful in that the Russian program has employed more complex models that use observational data iteratively, while the filter model is at a level of simplification better suited to data inversion.

The note reviews the filter model and exhibits and discusses its main scaling relationships. The comparison uses criteria defined by the PN, EN, SN, and Russian efforts to identify likely breakup candidates. It reviews the full released SN data base and extracts several useful scaling relationships. It discusses each of the SN objects for which light curves are available, preparing filter predictions for each object. These predictions are examined for correlations and correlated with the inferred values, with which they generally show good agreement. In particular, the diameters agree closely, which means that other derived quantities are expected to agree at least as well. The correlation of size with radiation pulse width is weaker, but does indicate a systematic increase of pulse width with diameter.

The 19 released satellite light curves are reviewed in some depth, as they illustrate a wealth of phenomena that could make interpretation either more complicated or simpler. An example is object 88106, whose high frequency structure suggests the possibility of decomposing the light curve in terms of individual fragment power functions. While a valuable source, the application of most of these curves is limited by their lack of an object speed, angle of incidence, or altitude of maximum radiation.

The seven objects for which trajectory information, radiation altitude, and Russian analyses are available are given detailed analysis, including numerical calculations to facilitate comparison. The most direct comparison is of the filter and inferred diameters and masses.

Figure 21 shows that the correlation is good for objects up to about 3 m across, but that for larger inferred masses, the filter masses are lower. The velocity correlations are weaker. However, there are only a few such objects.

Object 88106 is the most difficult to analyze. The power is modeled reasonably well by the inferred parameters; the total radiated energy is not. It appears necessary to account for the four distinct peak, and the tail, of the light curve to achieve good quantitative agreement on radiated energy. The filter works well without adjustment for both the largest objects and the smallest. It also works reasonably well for light curves with multiple humps, although the additional structure can degrade estimates of intermediate parameters. For most of the objects the sizes and masses agree to within 10-20%, as do the peak powers and total radiated energies.

Thus, the filter appears to give more than adequate estimates of object sizes, masses, and other parameters. In the interpretation of the signatures of unknown objects, it would appear to have two types of limitations: information and decomposition. The former refers to the filter's need for an estimate of the altitude of radiation. It can be addressed partially by varying the altitude in the light inversion, but the filter's sensitivity to altitude and density is strong. Thus, it would be useful to have information on altitude for more objects or at least an automated process for selecting the optimum altitude, which would presumably make use of more information from the light curve.

The issue of decomposition refers to the fact that individual fragments typically have widths of ~ 0.1 s, while collections of fragments have widths of ~ 0.6 s. Treating the mass if it was concentrated in a single fragment distorts the computed light curve in numerical calculations and the effective pulse width in filter analyses. At a minimum, using the ratio of the overall pulse width to the width of a single fragment as an estimate of the number of fragments, over which the mass is divided equally, has been shown to provide reasonable estimates for a variety of object sizes and pulse length. This problem of decomposition, which first appeared in the analysis the Benesov and Sumave bolides and which appeared again in 4-5 of the SN objects above, is clearly a fruitful area for further work. However, overall, the SN observations, like the PN and EN data analyzed earlier have been shown to provide a useful test of the filter model, a positive assessment of its fidelity, and a good basis for the comparison of the filter with other numerical analyses.

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Table I. SN parameters

Table 1.1

Assessment of kinetic energy of bolides E_0 using
theoretical values of integral efficiencies η_i
and detected energy of the light flashes E_r

Bolide data	P_m , W/sr	E_r , kt	η_i , %	E_0 , kt
88106	1.42E+12	1.79	10.7	15.9
90274	3.53E+11	0.57	9.7	5.88
91277	6.56E+10	0.14	8.4	1.66
93304 *	6.32E+09	0.0095	5.95	0.16
93333	1.05E+10	0.0063	5.58	0.11
94032	3.17E+12	4.39	11.5	38.0
94149	9.90E+10	0.090	8.00	1.12
94154	1.56E+11	0.12	8.26	1.45
94166 **	4.00E+09	0.0031	4.93	0.063
94227	2.71E+10	0.043	7.33	0.587
94265	6.50E+10	0.016	6.53	0.244
94281	2.20E+10	0.0157	6.51	0.241
94293	1.41E+10	0.021	6.68	0.314
94300	8.42E+10	0.077	7.86	0.979
94305	2.43E+11	0.36	9.26	3.87
94307	3.39E+11	0.56	9.67	5.79
94341	8.28E+09	0.0019	4.49	0.043
94347	1.13E+10	0.0029	4.87	0.059
94350	2.76E+10	0.0086	5.86	0.147
95002	7.50E+09	0.0071	5.79	0.123
95004	1.93E+10	0.044	7.35	0.598
95010	9.00E+09	0.006	5.63	0.106
95018	3.25E+10	0.022	6.72	0.327
95047A	1.50E+10	0.0042	5.21	0.081
95047B	1.00E+10	0.014	6.31	0.222
95092	1.20E+10	0.0060	5.63	0.106
95188	3.00E+10	0.0333	7.20	0.463
95190	6.20E+10	0.0595	7.73	0.770
95192	4.10E+10	0.031	7.13	0.434
95217	1.80E+10	0.0238	6.89	0.346
95218	2.40E+10	0.013	6.35	0.206
95229	1.60E+10	0.038	7.32	0.520
95236	2.70E+10	0.0286	7.06	0.405
95252	7.50E+10	0.119	8.36	1.420
95269	1.10E+10	0.0029	4.96	0.058
95274	2.10E+10	0.0083	5.93	0.140
95317	1.10E+10	0.005	5.47	0.091
95322	6.50E+09	0.0008	3.81	0.021
95323	5.50E+09	0.0024	4.79	0.050
95329	2.10E+10	0.0069	5.76	0.120
95343	4.70E+10	0.0286	7.06	0.405
95356	7.80E+10	0.107	8.26	1.297
95361	2.20E+10	0.083	8.03	1.04
96015	6.30E+10	0.067	7.83	0.851
96018	4.00E+10	0.0029	4.96	0.058
96046	2.00E+10	0.012	6.26	0.190
96047	1.70E+10	0.0076	5.85	0.130
96073	3.30E+10	0.055	7.65	0.716
96086	8.00E+09	0.002	4.64	0.044
96089	3.00E+10	0.021	6.77	0.309
96096	4.20E+10	0.0286	7.06	0.405

* - noisy,

** - Montreal, 10 Hz filtered, noisy, preliminary

Table II. SN DATA

no		P	PGWs	ErKT	rad eff t	rha	Vo	D	rha	z	rho	q	f	PmGW	tm	D	Vo km	S	
1	88106	#	890	11	0.11	0.45	3000	45000	3	3000	30	0.014	467	0.1	10680	0.45	4.17	32.7	250
2	90274	#	294	4.8	0.1	0.54	3000	20000	3.9	3000	30	0.014	467	0.1	3528	0.54	3.73	24.3	138
3	91277	#	50.5	0.95	0.08	0.5	3000	20000	2.3	3000	30	0.014	467	0.1	606	0.5	2.5	17.7	73
4	93304	#	6.32	0.095	0.05	0.25	3000	20000	1.1	3000	30	0.014	467	0.1	75.84	0.25	1.09	15.4	55.4
5	93333	#	10.5	0.063	0.04	0.09	3000	20000	0.9	3000	30	0.014	467	0.1	126	0.09	0.64	25.9	157
6	94032	#	3200	43	0.13	0.58	8000	20000	5.9	3000	30	0.014	467	0.1	38400	0.58	6.23	38.3	343
7	94149	#	99	0.9	0.08	0.24	3000	20000	2.3	3000	30	0.014	467	0.1	1188	0.24	1.83	27.2	173
8	94154	#	156	1.2	0.08	0.21	3000	20000	2.5	3000	30	0.014	467	0.1	1872	0.21	1.86	31.3	230
9	94166	#	5.2	0.11	0.05	0.37	3000	20000	1.1	3000	30	0.014	467	0.1	62.4	0.37	1.31	12.7	37.8
10	94227	#	27	0.43	0.07	0.37	3000	20000	1.8	3000	30	0.014	467	0.1	324	0.37	1.82	17.7	73.1
11	94293	#	14	0.21	0.06	0.3	3000	20000	1.4	3000	30	0.014	467	0.1	168	0.3	1.42	16.8	66
12	94300	#	84	0.77	0.08	0.24	3000	20000	2.2	3000	30	0.014	467	0.1	1008	0.24	1.76	26.5	164
13	94307	#	340	5.6	0.1	0.57	3000	20000	4.2	3000	30	0.014	467	0.1	4080	0.57	3.93	24.7	142
14	94347	#	11	0.029	0.03	0.03	3000	20000	0.7	3000	30	0.014	467	0.1	132	0.03	0.34	40.3	379
15	94350	#	28	0.086	0.05	0.05	3000	20000	1	3000	30	0.014	467	0.1	336	0.05	0.55	39.8	370
16	95004	#	19	0.44	0.07	0.53	3000	20000	1.8	3000	30	0.014	467	0.1	228	0.53	2.13	14.2	47.1
17	95018	#	33	0.22	0.06	0.13	3000	20000	1.4	3000	30	0.014	467	0.1	396	0.13	1.04	27.6	178
18	95047A	#	15	0.042	0.04	0.04	3000	20000	0.8	3000	30	0.014	467	0.1	180	0.04	0.41	39.6	366
19	95047B	#	10	0.14	0.06	0.26	3000	20000	1.2	3000	30	0.014	467	0.1	120	0.26	1.21	16.7	65.3
		#																	

Table III. Parameters for SN observations with altitude information.

Table 3.2

Parameters of SN events

Event	E_r , kt	P_m , W/sr	h_m , km	Model	E, kt	M, ton	V, km/s	η	η_i	Probable composition
88106 (SN2)				ARD	8-9	25-45	40-50	18-21		
15 Apr. 1988	1.70	$1.4 \cdot 10^{12}$	43	AP	8-9	25-45	48-50	18-21	11	stony
90274 (SN1)				ARD	5-8	100-300	15-20	7.1-11		
1 Oct. 1990	0.57	$3.5 \cdot 10^{11}$	30	AP	3-5	70-200	15-20	11-19	9.7	stony
91277 (SN3)				ARD	1.2-2	25-75	15-20	7-13		
4 Oct. 1991	0.14	$6.6 \cdot 10^{10}$	33	AP	0.9	20	15-20	15	8.4	stony
94032 (SN4)				ARD	40-70	1000-2500	15-20	6-14		
1 Febr. 1994	4.39	$3.2 \cdot 10^{12}$	34, 21	ARD	39	510	24*	11		iron
				AP	31	400	24*	14	12.5	
94149 (SN5)				ARD	0.6-2.5	2-140	< 50	3.5-15		
29 May 1994	0.090	$9.9 \cdot 10^{10}$	34	AP	0.6-2.5	2-140	< 50	3.5-15	8.0	—
**94307 (SN7)				ARD	5-8	100-300	15-20	7.1-11		
3 Nov. 1994	0.56	$3.4 \cdot 10^{11}$	30**	AP	3-5	70-200	15-20	11-19	9.7	stony
94350 (SN6)				ARD	0.07-0.3	0.25-17	< 40	3.3-14		
16 Dec. 1994	0.0086	$2.8 \cdot 10^{10}$	30	AP	0.07-0.3	0.25-17	< 40	3.3-14	5.9	—

* - Entry velocity became known,

** - Using a similarity to 90274 in E_r , P_m and a shape of the light curves.

Here E is the kinetic energy of the body, M is the mass, V is the velocity, E_r is the energy of the radiation impulse, P_m is the peak power of radiation, h_m is the height of breakup, η is the luminous efficiency ($\eta = E_r/E$), and η_i is the integral luminous efficiency from approximation of the simulation results averaged over the initial velocity, i.e. $\eta_i = 0.021 \log E_r + 0.103$.

SN data 7

Table IV. Filter parameters for SN objects for which altitude is known																		
tt obs	SN	Event	FPk GW	rad eff	rh	Er	Mo	Vo	KE	Di m	rha	z	rlq	f	ft	Da	Va	S bar
0.3	2	88106	900	0.19	43	1.62	35	45	8.9	2.8	3000	43	1182			1.75	71.2	109
0.5	1	90274	350	0.19	30	0.57	80	18	3.1	3.7	3000	30	467			3.23	22.9	72.3
0.5			350	0.11	30	0.55	130	18	5	4.4	3000	30	467			3.6	25.6	89.9
0.7	3	91277	66	0.15	33	0.14	20	19	0.9	2.3	3000	33	578			2.65	17.8	28.5
0.7	4A	94032	400	0.14	34	0.84	77	24	5.6	2.7	8000	34	1015			2.34	33.4	86.5
0.3	4B		3200	0.14	21	4.34	400	24	29	4.7	8000	21	401			3.51	33.9	571
0.15	5	94149	99	0.15	34	0.09	2.2	45	0.6	1.2	3000	34	621			1.1	37.9	112
0.15			99	0.04	34	0.09	10	45	2.5	1.9	3000	34	621			1.47	50.7	200
0.3	7B	94307	340	0.19	30	0.57	75	18	2.9	3.7	3000	30	467			2.36	27.9	108
0.3			340	0.11	30	0.55	130	18	5	4.4	3000	30	467			2.64	31.2	134
0.2	6	94350	28	0.14	30	0.01	1	25	0.1	0.8	3000	30	467			1.2	21.2	61.9
0.2			28	0.03	30	0.01	4	25	0.3	1.4	3000	30	467			1.6	28.3	110

Fig. 1. Er vs Pmax

Fig. 2. Radiation efficiency vs D_i

Fig. 3. Dappr vs Ddir

Fig. 4. D vs t

Fig. 6.1

Fig. 6.2

Fig. 6.3

Fig. 6.4

Fig. 6.5

Fig. 6.6.

Fig. 6.7

Fig. 6.8

Fig. 6.9

Fig. 6.10

Fig. 6.11

Fig. 6.12

Fig. 6.13

Fig. 6.14

Fig. 6.15

Fig. 6.16

D approx vs D inferred

$z \sim VVV$

V vs V

Fig. 23. P v t 88106

Fig. 24. P vs z 88106

Fig. 25. P v t 90274 SN 1

Fig. 26. P v z 90274 SN1

Fig. 27. P v t 91277 SN3

Fig. 28. P v t 94032 SN4

Fig. 29. P vs t 94149 SN5

Fig. 30. P v t 94307 SN7

Fig. 31. P v t 94350m SN6