INTERACTION OF LARGE BODIES WITH THE EARTH'S ATMOSPHERE

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During the last decade much work has proceeded on the problem of understanding the complex physiochemical processes associated with the entry of large meteoroids into the atmosphere. In this paper the respective areas of ablation, luminosity and infrasonic wave generation are surveyed from the viewpoint of the physics of fluids. Related work on meteorite cratering processes is not considered in this brief survey. Companion papers by Baggaley and by Ceplecha consider additional areas of current interest in meteor and fireball research.

ENTRY ABLATION MODELS AND OBSERVATIONAL CONSTRAINTS

Theoretical Entry Models

In this section recent theoretical entry models are summarized. In addition, a new method is proposed which has merit in helping to explain earlier results. Throughout this section except where otherwise noted, we assume that fragmentation effects can be reasonably ignored. This will be the case if either the total number of fragments is small or if most of the original mass is contained in only a very few fragments.

Basically there are three variations that have been proposed in the last decade in order to improve upon the simple ablation theory treatment (McIntosh 1970a). In two of these models the classical assumption of the equivalence of the heat transfer and drag cross-sectional areas has been relaxed and in the third a detailed altitude-time dependent model was developed without relaxing the classical model assumptions.

Padavet (1977, 1978) proposed a refined model, following the work of Petrov and Stulov (1975), that predicted that the effective drag area of an entering meteoroid will increase immensely due to the "slowness" of the removal of the ablated mass. The model of Petrov and Stulov is based on an ablation model in which turbulent mixing of ablated vapor

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and free stream air results in a build-up of ablated material such that the effective drag area produced increases the end height of a non-fragmented meteoroid considerably. In simple terms their model predicts that the rate of removal of ablated material is slower than the rate of ablation itself. Padavet originally proposed his model in order to explain the differences at any altitude between the computed photometric and dynamic masses. However, the detailed predictions of Padavet's model were found inadequate to explain the behavior of the three photographed and recovered meteorites (ReVelle and Rajan 1979).

Liu (1978) proposed a model of a porous meteoroid in order to explain the behavior of the Tunguska event of 1908. This was also the motivation behind Petrov and Stulov's work. In Liu's model only the heat transfer area increased as the proposed porosity of the body increased. As with Padavet, Liu considered the ablation parameter σ to be a fixed constant. Liu's model was developed partly because of the conclusion by Petrov and Stulov that there would be insufficient ablation predicted using conventional radiation gas dynamical treatments to adequately explain the behavior of the Tunguska meteoroid. Following the work of ReVelle (1979) and via the constraints imposed by cosmic ray track analysis of meteorites (Bhandari et al. 1978), such porosity assumptions are unnecessary for the bulk of the Prairie Network fireballs (Ceplecha and McCrosky 1976). The net effect predicted by the models of Liu and of Padavet respectively is that at the same height, for a given set of initial conditions, the former model would allow for significantly smaller mass values and the latter for much larger mass values than would be predicted by the simple ablation theory.

The final model which is a variant of the simple ablation theory treatment is that of ReVelle (1979). In this model all quantities are altitude dependent, with the exception of the shape factor, and radiative heating is calculated without assuming a priori the gas opacity at the stagnation point. Consistent with the simple theory, the drag and heat transfer areas are assumed to be equivalent. No attempt was made to predict fragmentation phenomena, but predictions of the initial mass of meteorites rely more on the value of the recovered mass than they do on the end height. The net upward movement of the end height in the presence of fragmentation relative to the single-body treatment is limited by the factor $N^{1/3}$ according to Baldwin and Sheaffer (1971) so that for $N \lesssim 10$, the end height increases by $\lesssim 5$ km due to the effect of the decreased mass to area ratio during the fragmentation process. ReVelle (1979) used this prediction as a constraint on the velocity versus height prediction, as compared to the observed variation, to aid in predicting the initial mass of the three photographed and recovered meteorites.

Recently Rajan, ReVelle and Wetherill (1978) have combined the predictions of ReVelle (1979) with the results of cosmic ray track analyses (Bhandari et al. 1978) in order to predict the entry velocity of a group of several carefully selected meteorites. The possibility of prediction of orbital elements via such a technique is obviously of great intrinsic interest.

Within the area of fragmentation modeling, Padavet (1973a, 1973b) has attempted a model which in some ways is similar in philosophy to the σ intersection method of McIntosh (1970b). The latter method can be used to predict both the initial mass and the effective ablation parameter of each fragment of photographed and recovered meteorite falls assuming that after fragmentation occurs each piece ablates in an independent manner. A similar approach was used by Renard and Cassidy (1971) to infer the initial mass of the Campo del Cielo Crater 9 Meteorite in Argentina. The inverse problem solution is not physically unique, however, and known limitations of the parameters in the analysis must be applied in order to constrain the result within reasonable limits (ReVelle 1979).

Padavet (1973a, 1973b) assumed such independent fragment behavior in the near wake of a fragmented meteoroid until finally the fragments separate away from the leader. Although this approach differs from the model of Baldwin and Sheaffer (1971), it is in agreement with the prediction that a decreased mass to area ratio of the leading fragment results in a higher end height. Even if the latter approach is basically correct, i.e., independent ablation versus the collective behavior proposed by Baldwin and Sheaffer (1971), we still have the problem of knowing both the triggering mechanism of the fragmentation process and the initial conditions for which the process begins. Both pressure loading (Baldwin and Sheaffer 1971) and heat loading models (Jones and Kaiser 1966; McCrosky and Ceplecha 1970) have been proposed previously, but a combination of these based on the work of ReVelle (1979), may also be inferred from the available data.

Bess (1979) developed a progressive fragmentation model in order to reconsider the detailed behavior of high density artificial meteoroids. These objects were originally used to infer the Trailblazer luminous efficiency results (Ceplecha and McCrosky 1976). Although the model of Bess needs considerable refinement, its combined use of dynamical and photometric data to infer fragmentation effects independent of any postulated destruction mechanism is extremely significant and deserves further consideration.

Recently it has become possible via very complex numerical methods to calculate stagnation point as well as non-stagnation mass loss rates (Sutton 1973; Sutton 1974; Sutton 1975; Moss et al. 1975; Sutton et al. 1975). The latter values do not constitute a physical theory prediction, but rather represent a steady state ablation rate which can be inferred directly as a result of the overall numerical procedures. This information is sufficiently detailed that the problem of calculating possible shape factor variations during entry can now be considered.

It has been known for some time that blunting is a result of the hypersonic drag interaction process. However, as is described by

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Minges (1969) a combination of blunting at the stagnation point and rounding off at positions nearly at right angles to the oncoming flow can also occur. The net result could be either a net equilibrium shape different from a sphere or possibly an oscillation between these two extremes. Such flattened shapes are also observed in certain meteorites (McCrosky et al. 1971) and inferred indirectly for their largest fragments using the σ intersection method of McIntosh (ReVelle 1979). We now proceed to analyze in a preliminary manner such possibilities. We begin by simplifying the problem via some useful and reasonable assumptions.

a. Initially the body is assumed to be spherical and not rotating. Rotation can be included in a simple manner later depending on the constancy of the axis of the plane of the rotation. If the rotational period is large compared to the time associated with the entry, then effectively the meteoroid can be considered as nonrotating for ablation calculations.

b. Consistent with the theory of ReVelle (1979) we have assumed that the thermal conduction process can be ignored. Presumably inclusion of this process will primarily result in a smoothing effect on the results obtained neglecting conduction. Greater details on a numerical method used to calculate shape change during hypersonic flow can be found in Tompkins et al. (1971).

c. The near-equilibrium heat transfer values of ReVelle (1979) are reliable and accurately model the flow at the stagnation point. When viewed in the context of the present analysis, the stagnation point model for a body of constant shape, without rotation, represents the maximum possible ablation case.

d. As the shape is allowed to change, neither the predicted heat transfer nor the drag coefficient as evaluated at the stagnation point are altered. This is clearly a first order effect as is shown in Tompkins et al. (1971) and needs to be incorporated in a more refined shape change model.

From the detailed numerical analyses we have discerned the following facts. First, the suggestion by Park (1978) that the local ablation rate is everywhere proportional to the local heat flux at non-stagnation point locations is generally confirmed. The only exceptions to this rule seem to be bodies of rather extreme initial shape at locations far from the stagnation point. Secondly, the form of both the heating pulse and consequently the ablation profile is very nearly Gaussian with its width correlating very well with the instantaneous velocity of the body. The peak of the Gaussian curve is at the stagnation point. In order to apply this model to the meteorites considered earlier by ReVelle (1979) we have had to modify the predicted ablation behavior slightly so that only one average shape change was predicted. This is in contrast to the more exact numerical model of

Tompkins et al. (1971) which predicted a shape change with time relative to the original shape.

Although full details will be reported elsewhere, the results of such computations as applied to the Lost City and Pribram meteorite entries exhibit two interesting features. First, a blunting effect is predicted in both cases so that a mean shape factor less than that of a sphere over the entire entry is appropriate. Secondly, the formation of an indentation near the stagnation point in the case of Pribram suggests the possibility of an additional triggering mechanism for the break-up of large bodies. Also, the resulting raised end height, even without considering fragmentation, due to a combination of shape change and consequent drag coefficient variation, makes the detailed behavior of the meteorite entries in ReVelle (1979) be in even better agreement with the observations at the presently deduced initial masses.

Other Constraints

There are at least two other ways of analyzing the possibilities of fireball behavior during entry. One is via the analysis of numerous data available from the fireball networks (Halliday 1973; Zotkin et al. 1976; Halliday et al. 1978). Such efforts have been attempted recently with differing conclusions (Bronshten 1976; Ceplecha and McCrosky 1976; ReVelle and Wetherill 1978a). A more complete analysis by the latter authors is currently being prepared and will be reported at a later date.

The second possibility is via the results of cosmic ray track analyses on meteorites. A comprehensive recent summary is provided in Bhandari et al. (1978). Their three basic conclusions are in generally quite good agreement with the entry model of ReVelle (1979). A slight disagreement pointed out by Goswami et al. (1978), although not completely resolved, is such that if the rare-gas studies of the Innisfree meteorite are considered, only about a factor of two discrepancy in initial mass between the methods is found (see also the following section). Considering the complex nature of the problem, this is about as good agreement as might be expected. It is considered significant that in contrast to the photometric methods which indicate mass loss rates $\gtrsim$ 90 to 95 percent, independent of the meteor velocity, the model of ReVelle (1979) and the observations of Bhandari et al. (1978) both find rates ~ 30 to 99 percent with a strong velocity dependence.

LUMINOSITY APPROACHES

Theoretical Models

About fifty years ago Öpik (1933) introduced the concept of the luminous efficiency (instantaneous value). He then proceeded to calculate via complex quantum mechanical methods, the expected value of the

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luminous efficiency for meteoroids experiencing free molecular flow. Whipple (1943) greatly simplified Öpik's tabular results into one simple expression which has since provided the principal means for calculating the photometric mass. Although numerous simulation experiments have been performed in the atmosphere and in laboratories, no real general concensus has been achieved in this area. Recently Kovshun (1977) has summarized the work done for meteoroids experiencing free molecular flow. Also, ReVelle and Rajan (1979) have deduced values of luminous efficiency via an empirical technique utilizing light data from the three photographed and recovered meteorites using the theoretical ablation rates determined by ReVelle (1979). In an attempt to predict the integral value of the luminous efficiency, ReVelle (1980) used a completely macroscopic theoretical approach. Here we are considering the integral of the light curve compared to the predicted kinetic energy change in contrast to the differential or instantaneous value considered previously. Assuming that the single-body model is applicable and that the ratios of the various efficiencies of light, heat, ionization, etc., are known (Romig 1965) and constant, values of the integral luminous efficiency can be predicted.

Depending on the color index for such bright events, we find agreement between this macroscopic approach and the equivalent values calculated from the data in ReVelle and Rajan (1979). Recent work by Stohl and Hajdukova (1979) have cast doubt on the value -2 for the color index of bright events. Using a value of zero which is close to that indicated to the author by Ceplecha (private communication 1978) and the absolute energy conversion factor 10^A with A = 9.72 we find the integral value of the luminous efficiency to be 1.0, 2.2 and 4.1% for Lost City, Innisfree and Pribram respectively using the initial mass values deduced by ReVelle (1979).

Not considering fragmentation, this approach would indicate an upper limit to the mass of the Innisfree meteorite of ≃ 44 kg if the integral luminous efficiency of Lost City and Innisfree are really the same and ≃ 1% at the end height as indicated by the recent theory. Similar arguments would lead to a maximum initial mass for the Pribram meteorite of ~ 5500 kg. Limits on the altitude behavior of luminous efficiency can also now be set using ReVelle's recent model. Interestingly, the model also predicts a very weak dependence of the integral luminous efficiency on the body's mass. Although the single-body approach is not strictly valid for all fireballs, for ~ 1/3 which appear to be meteoritic (Ceplecha and McCrosky 1976; ReVelle and Wetherill 1978a), we now appear to have a good starting point for further analysis.

Additional Considerations

As summarized recently in ReVelle and Rajan (1979) much more work needs to be done to simulate via laboratory and atmospheric entry techniques the processes involved and to extend the results of these

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experiments to even greater velocities, body sizes and types of materials. In addition, future experiments should be planned to determine an energy balance statement for the various forms generated. In this way the macroscopic theory proposed by ReVelle (1980) can be more adequately tested.

Finally, it is noted that additional topics related to meteor luminosity have not been considered in this brief survey. These include the areas of fireball spectra, remnant meteor train luminosity and its associated flow chemistry and infrared satellite observations of fireballs, etc. Data from the latter topic is not generally available in the literature, but has been briefly documented for the daylight fireball of August 10, 1972 by Rawcliffe et al. (1974) and more recently for three additional fireballs observed by Rawcliffe (private communication 1978).

AIRWAVES FROM LARGE METEOROIDS

Summary of Available Data

During the last decade the number of available recordings of airwaves from large meteoroids has increased almost twenty times. The barograph recordings of the Tunguska event of 1908 (Whipple 1930) have stimulated much scientific interest, but it has only been in recent years that scientists have had access to a much larger body of airwave data and the techniques necessary to adequately study them. The term airwave refers to the infrasonic or acoustic-gravity waves launched during the hypersonic entry of a large meteoroid into the atmosphere. The dominant source of such waves is presumably the remnant of the line source blast wave generated during entry, although a terminal explosion or break-up via a violent fragmentation process at low altitudes may be a more realistic source model for some of the observations.

Since many of the airwaves recorded in recent years have already been well documented in the literature, we will only deal here with those which have not been generally available. Details about the former events can be obtained in the papers of ReVelle (1976) and McIntosh, Watson and ReVelle (1976).

Treating the latter events historically in terms of their availability, we have the following record:

a. Infrasonic recording of Prairie Network fireball No. 42556 in Sioux Falls, South Dakota in May, 1976, by Bartman and Kraemer (private communication with F. L. Bartman 1976). This event is classified by Ceplecha and McCrosky (1976) as Group II (carbonaceous chondrite) and has a scaled end height of 23.5 km (ReVelle and Wetherill 1978a), compared to 21.5 km for the Lost City and Innisfree Meteorites. Although the full details will be published elsewhere, the basic data of interest are: Wave period at maximum signal amplitude (~ 1.4 to

2.3 μbar) is ~ .21-.22 seconds at a range ~ 120 km from a source height ~ 60 to 65 km.

b. A series of recordings made by AFTAC from 1960 to 1974 via a global array of microbarographs (Shoemaker and Lowery 1967; Gault 1970; ReVelle and Wetherill 1978b). These data include airwaves from the well known Revelstoke meteorite, a Type I carbonaceous chondrite. In addition, although the data have not been located by AFTAC, through contacts with Goerke (private communication 1972) and with Whipple (private communication 1975), it was made clear that airwaves from the August 10, 1972 event referred to earlier have also been recorded. Interestingly, however, two ground based arrays affiliated with NOAA failed to detect this major event, probably due to local refraction effects (private communication with A. J. Bedard 1977).

c. Recordings of the airwaves from the Revelstoke meteorite taken in conjunction with seismic observations at multiple stations as part of Project Vela Uniform (Bayer and Jordan 1967; private communication with J. N. Jordan 1977).

d. Additional recordings made at the Wave Propagation Laboratory of NOAA, Boulder, Colorado, which have not yet been totally analyzed (private communication with A. J. Bedard 1977). These include data from a possible meteorite fall over Texas in 1975 (private communication with O. Monnig 1975).

Although in general the air-coupled Rayleigh waves generated by large meteoroids have not been considered here, data from a recent well documented event of this type is given in Nagasawa (1978).

Source and Propagation Models

We can identify three possible types of source modeling of airwaves from large meteoroids:

a. Line source cylindrical blast wave models (Lung et al. 1975; ReVelle 1976; Golitsyn et al. 1977).

b. Modified line source models (Boyarkina and Bronshten 1976; Bronshten and Boyarkina 1975; Korobeinikov et al. 1976; Shurshalov 1978).

c. Point source models (Pierce and Kinney 1976).

Due to the complexity of both the source modeling procedures and the propagation variability in the atmospheric medium, attempts to use any of the above at great distances from the source to deduce source energy, for example, are subject to at least an order of magnitude uncertainty (Posey and Pierce 1971; Flores and Vega 1975). In the absence of a suitable physical theory for the combined variable-height source propagation problem, much reliance has been put on empirical approaches. One such approach, which is the final result of acoustic regression analyses on numerous low altitude "point" source U.S. nuclear explosions, can be expressed in equation form as (private communication with G. Leies 1978):

$$\log_{10}\left(\frac{E_S}{2}\right) = 3.34 \log_{10} P - 2.58; \quad \frac{E_S}{2} \leq 10^2 KT \tag{1}$$

$$\log_{10}\left(\frac{E_S}{2}\right) = 4.14 \log_{10} P - 3.61; \quad \frac{E_S}{2} > 40KT \tag{2}$$

where

E_S is the source energy in KT TNT equivalent (1KT $\simeq 4.2 \cdot 10^{19}$ ergs), with a quoted uncertainty of $\pm$ 100% in E_S.

P is the wave period at maximum signal amplitude (in seconds).

In (1) and (2) we have replaced the "yield" of a nuclear explosion by the factor $.5E_S$ using data provided in Pierce and Posey (1971). The factor of 1/2 comes from the large amount of radiation given off following a nuclear event in contrast to a more reasonable, very small fraction as determined using fireball data without significant flares (ReVelle and Rajan 1979).

In the AFTAC analysis of the meteoroid events, (2) was used for those events whose energies exceeded 40 KT and a relation similar to (1) was used for source energies $\lesssim$ 40KT. The energies of the events considered in ReVelle and Wetherill (1978b) were obtained in this manner, equating the "yield" to E_S.

Data Interpretation

If we reconsider the work of ReVelle and Wetherill (1978b) and now allow for two additional possibilities not previously considered, we can hope to improve upon and possibly reduce the uncertainty in the previous estimates of the global flux rate of large meteoroids. During the past decade or so this problem has been considered by Shoemaker and Lowery (1967) (as discussed briefly in Gault (1970)) using airwaves from large meteoroids, by McCrosky (1968) using photometric studies of the Prairie Network fireballs, by Latham et al. (1972), Duennebier and Sutton, (1974) and by Duennebier et al. (1975) using lunar seismograph recordings and by Baggaley (1978) using British fireball reports. Estimates of the flux rate in the past have varied over about two orders of magnitude considering the same mass range.

Using the AFTAC data and the corresponding energy values deduced using (1) and (2), ReVelle and Wetherill (1978b) found a total energy arriving at the earth's orbit of $2.1 \cdot 10^{21}$ ergs/year. This is the integrated amount in the mass range 10^6 to 10^{10} grams. The equation describing the steady state flux as a function of the integrated number of meteoroids per year over the entire earth whose source energy was $\geq$

E_S was found for ten events to be (if $E_S/2 \equiv$ Yield in KT TNT):

$$N(E_S) \cong 10.4 E_S^{-.87} \qquad (3)$$

using global percent coverage values provided to us by AFTAC.

Equation (3) can be modified by allowing for the following:

a. If the real end height is not at the surface, E_S has probably been overestimated. This can be corrected assuming a point source blast wave scaling law for the period produced at maximum signal amplitude. Using the Revelstoke meteorite as a calibration with an end height of 12 km (Folinsbee, et al. 1967) and assuming this value applies to all the events recorded, we find that E_S determined previously was over-estimated by ~ 4.95 times (assuming refraction effects by temperature and wind gradients in the atmosphere can be neglected).

b. If the energy E_S is not indicative of the pre-atmospheric value, then the previously inferred flux rate was probably too low. This value could range from ~ 1 to $10^{-2} \cdot E_{SE}$, with E_{SE} the kinetic energy of the meteoroid at the "top" of the atmosphere. Assuming $E_S = .2E_{SE}$ as a relatively conservative estimate and also similar to the value used by Boyarkina and Bronshten (1976) for the Tunguska meteoroid event, we can determine the influence of this possibility on the computed flux rate.

Using the modifications suggested in a. and b. above, we find equation (3) is virtually the same with the constant 10.4 becoming 10.5 for these assumed parameters. Using a. and b., but using Tunguska as a calibration with an end height of 5 km and $E_S = .5E_{SE}$ (Bronshten 1976; Boyarkina and Bronshten 1976), (3) is also virtually unchanged. Again, using the latter authors' estimates of E_{SE} of 23.8 to ~ 100 MT TNT equivalent, we find that Tunguska type events could reoccur on a time scale ~ 600 to 3000 years over the entire earth. An extrapolation of the data of McCrosky (1968) would indicate the reoccurrence of such events once every 2.4 years which is clearly unrealistic. Part of the discrepancy is probably due to the photometric mass values used by McCrosky in computing the preatmospheric kinetic energy values.

Much more work needs to be done toward refinement of modeling necessary to predict the global influx rate. Predictions made using equation (3) are in reasonable agreement with other very dissimilar methods, however, and should probably be regarded as a reasonable estimate of the steady state global influx. The significant disagreement between the current results and the early prediction of Shoemaker and Lowery (1967) is not completely understood, but seems to be related to both a changeover in the empirical energy calibration scaling used to interpret the data (G. Leies private communication 1977) and to a slightly different original set of meteoroid airwave records (E. M. Shoemaker private communication 1979).

Further efforts along these lines will help to constrain estimates of the cratering time scale of the inner solar system (Wetherill, 1976) via a more accurate estimate of the present global influx rate of large meteoroids.

SUMMARY AND CONCLUSION

In this paper we have attempted a survey of recent work on the complex processes which accompany large meteoroid entry into the atmosphere. Specifically, the areas of ablation, luminosity and infrasonic wave generation were considered in detail. Further efforts in these and other areas may help to clarify further the detailed relationships between such bodies and the evolution and maintenance of our solar system.

Due to space limitations, the complete text as presented at the symposium could not be included in this volume. A copy of the complete paper is available from the author upon request.

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DISCUSSION

Keay: Additional independent evidence for the ablation process you described comes from the titanium high-pressure fuel tanks from Soviet spacecraft which have landed in Australia. In most cases the tank reenters nearly intact: its attitude is stabilized by a pipe fitting at one pole of the sphere; the opposite end, which faces forward as it reenters, ablates leaving a perfectly round hole. About 30% of the tank mass is lost. If the tank explodes before reentry (as with Cosmos 758) the fragments flutter during reentry with severe heating around the edges but no loss of mass by ablation.

Halliday: Your recent plots indicate that the type I and II fireballs seem to penetrate the atmosphere equally well under similar entry conditions. If we provisionally associate these groups with ordinary [I] and carbonaceous [II] chondrites, since we know both classes must be arriving, do you think the more severe fragmentation expected for carbonaceous chondrites could be related to the blending of the groups?
ReVelle: First I should say that although we can be certain that both carbonaceous and ordinary chondrites exist among the fireballs, I am not at all convinced that the Groups I and II of Ceplecha and McCrosky are correctly associated with these two types of materials. Their assumption relating bulk density to ablation energy is not defensible if we consider the laboratory data on meteorite samples used in my entry model. This assumption was necessary to separate Group I from Group II from the initial large number of deeply penetrating objects. It is possible that the severe fragmentation expected for carbonaceous material could mask somewhat the "real" initial mass so as to "blend" the mass values deduced. The end height is an observed fact and if it is correct (to ± 1 km, say) in all cases, then I am surprised that there

is no systematic deviation away from the curve as we go to larger fireballs since fragmentation should raise the end height. The other fact to keep in mind is that Group II has a mean height about 10 km higher than Group I and that such a large height difference is not justified by the model. Interestingly, most of the deviation from the theoretical curve is in the small mass range typical of meteors rather than in the fireball size range.

Cook: Where do you place the boundary between McCrosky's flux curve and the much lower one for extremely large events?
ReVelle: The wide latitude in interpretation of both of these sets of data militates against any reliable answer to your question. I have to be satisfied with the answer to the problem of photometric mass calibration before I accept McCrosky's flux curve as correct. Both the airwave data and McCrosky's data contain some fragile and some solid types of materials but in what proportions is not yet completely known in either of the mass ranges. For the large bodies, Yield=$E_S/2$ assumes fragile structure, whereas Yield=E_S is a better approximation for solid material. The difference between these two extremes is only a factor of two which is not enough to force the large-body flux to meet McCrosky's. Only a very extreme assumption such as $E_S=E_{SE}/100$ (and an average end height of 12 km) will cause the two curves to meet.

Millman: You mention having eliminated 30 fireballs from your plots because of lack of deceleration information. This would tend to eliminate those objects with high end points and I am interested to know what percentage of the total number plotted these represent.
ReVelle: We have adequate deceleration data for 286 of the 322 Prairie Network fireballs observed by McCrosky and coworkers. Of the 36 not considered, 6 were eliminated because they had spurious single-value decelerations comparable to the acceleration of gravity and thus produced very unrealistic dynamic masses. Thus only 10% of the total number plotted were left out because of no available deceleration data.

Kresák: Is it true that your initial mass for Innisfree is as low as 5 kg?
ReVelle: This is the initial dynamic mass calculated using deceleration data and assuming a shape factor, et cetera. In general I find that the deduced dynamic mass is three to four times smaller than the initial mass I deduce using velocity versus height data combined with the recovered meteorite mass. It is smaller presumably due to fragmentation effects.

Reply to *Hughes*: I agree with your (Brown and Hughes: 1978, Nature) estimate that a Tunguska event will occur every two or three thousand years. But I question the need to assume a fragile object because the calculated aerodynamic pressure at the end height is 10^8 to 19^9 dyne cm^{-2} which is sufficient to fracture stony bodies.