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Mass and penetration depth of Shoemaker-Levy 9 fragments from time-resolved photometry

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Abstract. Computational simulations of the first 100 seconds of interaction of Shoemaker-Levy 9 fragments with the Jovian atmosphere have revealed a potential method for estimating the masses and penetration depths of the individual objects. For sufficiently large fragments, impact-generated fireballs will rise into line-of-sight over the Jovian limb (less than one minute after impact for a 3-km diameter fragment). It is possible that time-resolved radiometric measurements from Earth- and orbital-based observatories may detect two different arrivals for each impact: first the shock wave and, a few seconds later, a debris front (fireball). Measurements of one or both arrival times with time resolutions of better than one second will provide information that would place strong restrictions on the range of values of equivalent explosive yield (from which fragment mass can be extracted) and effective penetration depth. We believe that time-resolved photometry measurements of impact-induced light emission (impact-flash signatures) will provide the best means by which Shoemaker-Levy 9 fragment masses can be determined if they are greater than about 5×10^{15} g (corresponding to a 1-km diameter ice sphere).

Introduction

The trajectories of approximately twenty fragments of periodic comet Shoemaker-Levy 9 are quite well known, so the times, locations, velocities, and angles of incidence of their impacts onto Jupiter have been predicted to a high degree of precision (Chodas and Yeomans, unpublished data, June 3, 1994). The most important parameter that is not known is the mass of each fragment, and it is doubtful that it will be possible to ever extract that information with much accuracy from pre-impact images because so many assumptions are required [*e.g. Weaver,* 1994].

The impact events have been modeled by several groups [*Crawford et al.,* 1994; *Takata et al.,* 1994; *Mac Low & Zahnle,* 1994; *Moran & Tipton,* 1993; *Vickery,* 1993; *Ivanov & Melosh,* 1994; *Sekanina,* 1993; Wingate, personal communication, 1994]. There is general agreement among most of these simulations as to the sequence of events, and on many the *qualitative* aspects of the entry, breakup, deposition of energy, and plume/fireball growth, but the *details* of the comet interaction sequence is still the subject of some debate. Aspects of the interaction on which there is still disagreement include the dominant instabilities that lead to breakup, the depth of penetration of a given fragment, and the intensity and spectral content of the radiative signatures.

The purpose of this paper is to point out what we regard as the most significant measurements that should be made to estimate fragment masses (from equivalent explosive yield) and depths of penetration. Knowledge of fragment masses is necessary to validate breakup models of the parent comet during its final (1992) perijove, and their independent determination would also be extremely useful to modelers of many post-impact phenomena. Determination of equivalent explosive yield and depth of penetration would provide the source function or focal mechanism for seismic modeling [*e.g. Marley,* 1994] and atmospheric wave effects [*e.g. Harrington et al.,* 1994; *Ingersoll et al.,* 1994]. In this paper we show that there are well-defined events (arrivals at the limb) that, if observed, can be used to estimate impactor mass and penetration depth.

Phenomena and Definitions

An observable impact event of this scale is unprecedented; the resulting phenomena have never before been witnessed. Because of this, the different modeling groups have not been using the same terminology to describe the phenomena. Unless careful definitions are made, this is likely to lead to considerable confusion.

When the comet fragment enters the Jovian atmosphere, it deposits its kinetic energy and material along its trajectory down to some maximum penetration depth. This leaves a long cylinder of very hot, high pressure atmosphere contaminated by cometary material. It explodes most rapidly back upward along the entry trajectory and the ambient pressure gradient. A mass of the contaminated atmosphere is ballistically ejected upward, expanding as it goes. It pushes a layer of atmosphere ahead of it, generating a shock wave similar to a bow shock. We call the upper boundary of the mass of contaminated atmosphere the "debris front". At early times, when the mass of contaminated atmosphere is hot and incandescent, we refer to it as the "fireball". After it expands and cools, we refer to it as the "debris cloud". Other groups [e.g. *Takata et al.,* 1994; *Mac Low & Zahnle,* 1994] have been using the word "plume" to describe the expansion-driven flow field.

We use "impact flash" to refer to the transient emission of light (including ultraviolet and infrared components) from the entire event, including the explosively-produced fireball and shock wave. "Entry flash" refers to the part of the impact flash generated by the penetrating bolide before it breaks up.

Numerical Simulations

Our simulations were performed in two steps: the two-dimensional axisymmetric penetration phase and the three-dimensional fireball calculation. We used the CTH multi-material Eulerian shock-physics code [*McGlaun, et al.,* 1990] for the penetration phase, to simulate the entry, deformation, and breakup of the impacting comet fragments without radiative transport. We used a "reverse ballistic" reference frame in which a scaled Jovian atmosphere was rammed upward at 60 km/s into an initially-stationary comet. Periodic Galilean transformations were used to maintain the comet fragment in the high-resolution (25 zones across the comet radius) portion of an Eulerian mesh which extended 100

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km radially and 1000 km vertically in each direction. We extended the mesh upward so that we could preserve the materials, state variables, and velocity fields for insertion into the subsequent three-dimensional simulation.

The simulated fragment was composed of water ice with an initial density of 0.95 g/cm^3 and with a temperature of 100 K. We made use of an ANEOS table [*Thompson*, 1989] for ice, which provides an equation of state that includes thermal expansion, melting, and vaporization. We used an atmospheric model derived directly from Voyager data (Orton, unpublished data, 1994), which we extrapolated downward adiabatically. The equation of state was constructed by Kerley (personal communication, 1994) for a mixture of 89% hydrogen with 11% helium. The resulting table of states includes dissociation and ionization.

We determined the energy deposited by comet fragments of various sizes and shapes during their penetration of the Jovian atmosphere [*Crawford et al.*, 1994]. A linear energy density as a function of depth was determined by summing the total energy contained within discrete altitude bands (3-25 km in thickness) of the computational mesh and normalizing by band thickness, and removing the initial atmospheric contribution (Figure 1). From these curves, a depth of maximum energy deposition can be determined, which we equate to the effective penetration depth. A spatially-averaged set of density, temperature, fluid velocity and pressure fields of the cometary debris and Jovian atmosphere were inclined 45° and inserted into a three-dimensional mesh to initiate the fireball simulation.

The fireball simulations were run on Sandia's Intel Paragon, an 1840-processor massively parallel supercomputer, using PCTH, a parallel version of the CTH Eulerian shock-physics code. The 3-D, bilaterally symmetric calculations simulated the evolution of

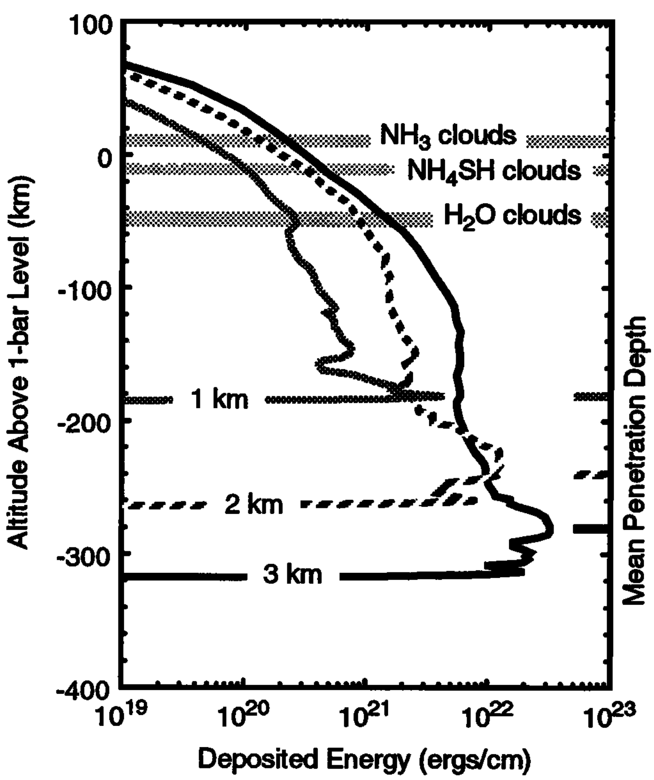

Figure 1. Energy deposited by ice spheres of various diameters during their penetration of the Jovian atmosphere. Mean penetration depths, defined by the depth of maximum penetration, are noted.

the fireball and shock front for up to 100 seconds after the first contact of the fragment with the atmosphere. The simulation of fireballs formed by the impact of 1- and 3-km diameter comet fragments required 8.0 and 6.3 million cubical computational zones and had resolutions of 3 and 5 km per zone, respectively.

Results and Discussion

The most important parameter that controls the depth of penetration of a given fragment is its mass. We performed a series of simulations to study the effects of shape, strength, and density, as summarized by *Crawford et al.*, [1994]. All of these parameters significantly influence the depth of penetration to varying degrees, but the fragment mass is the controlling factor for reasonable values of the other parameters. For large, full-density ice spheres, the penetration depth is relatively independent of yield strength up to 100 bars. Mean penetration depths for 2 and 3-km diameter fragments are about 240 and 280 km below the 1-bar level, respectively. For smaller fragments, the mean penetration depth is more dependent on yield strength. A 1-km fragment with 100-bar yield strength penetrated to 180 km, whereas a zero-strength fragment penetrated to only 130 km.

These penetration depths are somewhat greater than those of *Mac Low & Zahnle* [1994], and less than those of *Takata et al.* [1994]. We believe the reason for the shallower penetrations of the *Mac Low & Zahnle* [1994] simulations is due to the difference in equation of state used for the fragment. They have used ideal gas and other compressible fluid equations of state, which require confinement to prevent expansion. When the simulations begin, the unconfined fragment expands to lower density at the very first stages of interaction. Thus the effective density of the fragment is less than its initial density and it does not penetrate as far as it would if it had remained at its initial density, as it would if a more realistic equation of state for condensed matter had been used. The deeper penetrations of the *Takata et al.* [1994] simulations are harder to explain; however, benchmark comparisons (using a simplified comet/Jupiter impact problem) between our CTH runs and SPH simulations performed at Los Alamos (Wingate, personal communication, 1994) show that for an identical set of conditions, and with similar computational resolution, SPH predicts deeper penetrations. We conjecture that the differences are inherent in the two different numerical modeling techniques.

The fireball/plume simulations among the various groups are more difficult to compare, but the qualitative agreement is surprising. The *Mac Low & Zahnle* [1994] simulation is highly resolved, but is not a realistic simulation of the actual event because it is 2-D axisymmetric and assumes a vertical impact angle. The *Takata et al.* [1994] simulation is a better representation of the actual geometry, but has about two orders of magnitude fewer computational elements than ours. Because of these geometric and resolution issues, we are confident that our simulations can provide the most accurate representation of the shock and debris front evolution. Because of this, we are basing our predictions solely on the output of our computational simulations. If the shock front and fireball are sufficiently luminous, then their arrival times above the limb of Jupiter can be determined, and our predictions can be directly validated.

Predictions

We have completed high-resolution fireball simulations for 3-km and 1-km diameter ice fragments. For the 1-km ice sphere, the fireball will still rise above the limb of Jupiter; however, its temperature (about 600 K average above the limb) will be significantly lower than that for the 3-km fragment fireball (about 2000 K). The temperature at the shock front will be about the same in both cases (about 2000 K). Figure 2 shows the altitude of the shock and debris fronts plotted as a function of time after impact, where t=0 is defined as the time at which the fragment passes 100 km above the 1 bar level (where our simulations began). The line-of-sight elevations above the impact point for various angles beyond the limb have been added for reference. Line-of-sight elevations for the fragments have been indicated based on *Chodas and Yeomans* (unpublished data, June 3, 1994). Temperatures at the front of both the shock wave and fireball are listed at selected times during fireball growth.

In principle, shock or debris front velocities could be obtained by measuring shock and fireball arrivals from multiple vantage points with much better time resolution (sub-millisecond). Parallax for Earth-based observers located one Earth-radius apart corresponds to about 50 meters at the shock/debris front locations (a distance covered in 5-10 ms by the shock wave as it passes the limb). If the velocity of either the shock or debris front is precisely determined by limb arrival measurements, the equivalent explosive yield and penetration depth can be obtained from our simulations. These values can also be compared to those extracted using similarity solutions of the type pioneered by G.I. Taylor for point explosions [*Taylor*, 1950]. This would provide enough information to determine fragment masses, and allow the computational simulations to be validated.

Observational Requirements

The potentially observable events we predict are presented schematically in Figure 3. The shock wave and debris front (fireball) will both break above the limb at a point very close to the fragment trajectory. If times of arrival of one or both fronts are measured with coarse (sub-second) resolution using time-resolved photometry, they can be compared to the predicted values from Figure 2 to estimate the mass and penetration depth of the comet fragment. As described above, with precise (sub-millisecond) absolute timing, photometry records correlated from various locations would allow shock and particle velocities to be determined from the shock and debris front arrivals, respectively. Coupled with time interval determinations, this would make it possible to simultaneously determine equivalent explosive yield and penetration depth while validating the model.

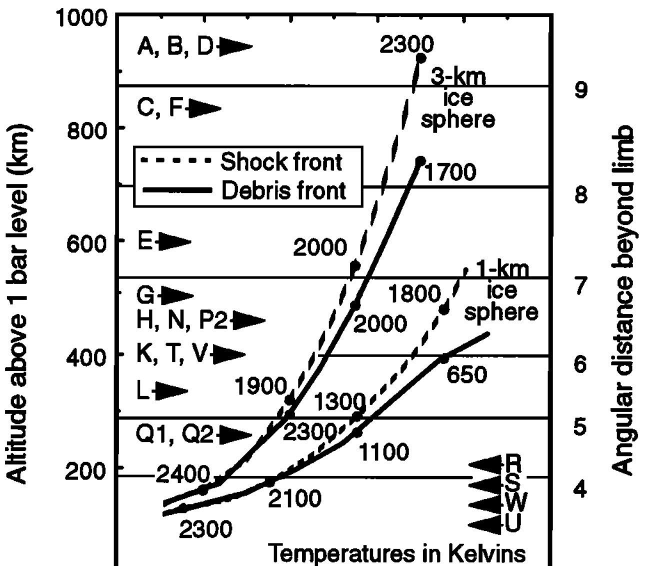

Figure 2. Altitude of shock and debris (fireball) fronts as a function of time for 3-km and 1-km diameter ice spheres, from three-dimensional simulations. If arrival times of these fronts above the limb are measured, then these curves can be used to extract fragment masses and penetration depths. Temperatures at both fronts are listed at selected times after impact. Altitude can be equated to a minimum line-of-sight elevation above the limb a given angle beyond the limb, given on the right-hand scale. Approximate line-of-sight elevations are shown for each fragment.

There is significant disagreement on whether or not the initial shock will be visible. Despite its high temperature (about 2000 K) the calculations of *Mac Low & Zahnle* [1994] predict it will be transparent. However, by using the Saha equations for those calculations, thermodynamic equilibrium conditions behind the shock front were assumed. There are many cases in which shocked gases become luminous by non-equilibrium processes. For example, the TEAK high-altitude nuclear test in 1958 generated a spherical shock wave that was made luminous due to an electronic transition in oxygen. The luminous sphere was visible from Hawaii, 11° over the horizon. Six minutes after the explosion it was still visible, and was 1000 km in diameter [*Glasstone & Dolan*, 1977]. Such shock-induced nonequilibrium phenomena are difficult to predict in advance. In addition, even the shocked atmosphere ahead of the debris front will contain amounts of cometary material which may significantly increase its opacity. This cometary material will have been deposited earlier by the infalling dust cloud surrounding the fragments, and by material stripped from the fragment on its way down.

It is generally agreed that the fireball itself will be opaque and luminous. Its arrival past the limb should be marked by a rapid change in both intensity and spectral content of light emission. If these events are sufficiently luminous, precise measurement at the limb of the entry meteor, shock front, and debris front (fireball) would be possible. We believe that because the limb masks direct light generated from beneath the line-of-sight elevation, the times of arrival at that altitude can be determined from time dependence of the impact flash as viewed from Earth. Thus, Earth-based photometric measurements will carry useful information that is not present in the impact flash signatures measured from Jovian satellite reflections or by direct line of sight from space probes. In principle, useful information can be extracted from direct measurement of shock-induced light emissions, but even simple one-dimensional models require assumptions and can yield non-unique solutions [*Boslough*, 1985]. The fact that Jupiter's limb masks all light emitted from below a certain altitude allows definite timing of arrivals, which is not possible for direct line-of-sight measurements. We have also suggested that the emergence of the debris cloud into sunlight may be observable, providing another point on its trajectory (Boslough et al., submitted to EOS, 1994).

We recognize that the probability of success is relatively low in determining fireball velocities by measuring their arrival times above the limb with sub-millisecond resolution, but the potential payoff is sufficiently high that every effort should be made to attempt them. However, even approximate (second-scale) measurements of limb arrival times would significantly constrain the possible values of mass and penetration depth, so we recommend time-resolved photometry of the Jovian limb as the most useful Earth-based measurements that could be made during the first few minutes after impact.

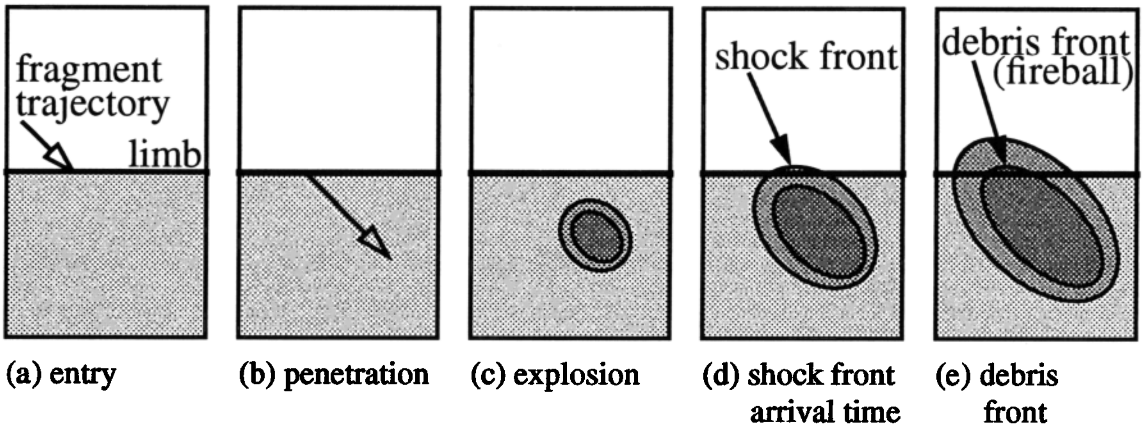

Figure 3. Schematic depiction of predicted events. (a) Comet fragment passes limb at time t_o. (b) Comet reaches maximum penetration depth. (c) Fireball is obscured by Jupiter. (d) Shock front passes limb at time t_s with shock velocity U_s. (e) Debris front (fireball) passes limb at time t_p with particle velocity u_p. It may be possible to determine times t_o, t_s, and t_p directly from time-resolved photometric observations. In principle, U_s and u_p could be extracted from parallax among Earth-based viewing positions.

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