For Space 96: The Fifth International Conference and Exposition on Engineering, Construction, and Operations in Space, Albuquerque, NM, June 1 - June 6, 1996. CONF-9606105--1

IMPACT-GENERATED ATMOSPHERIC PLUMES: THE THREAT TO SATELLITES IN LOW-EARTH ORBIT

M. B. Boslough and D. A. Crawford

Sandia National Laboratories, Albuquerque, New Mexico

ABSTRACT

Computational simulations of the impacts of comet Shoemaker-Levy 9 (SL9) fragments on Jupiter provide a framework for interpreting the observations. A reasonably consistent picture has emerged, along with a more detailed understanding of atmospheric collisional processes. The knowledge gained from the observations and simulations of SL9 has led us to consider the threat of impact-generated plumes to satellites in low-Earth orbit (LEO). Preliminary simulations suggest that impacts of a size that recur about once per century on Earth generate plumes that rise to nearly 1000 km over an area thousands of km in diameter. Detailed modeling of such plumes is needed to quantify this threat to satellites in LEO. Careful observations of high-energy atmospheric entry events using both satellite and ground-based instruments would provide validation for these computational models.

INTRODUCTION

The multiple impacts of comet SL9 fragments with Jupiter in July 1994 provided an historic opportunity to directly observe the phenomena resulting from hypervelocity collisions on a planet. Detailed analysis of this event has advanced our understanding of comets, of Jupiter, and of the collisional processes that shaped the solar system. This improved understanding can now be used develop better models for the assessment of the impact threat to Earth.

The principal reason we performed computational simulations of the SL9 impacts was to take advantage of a "natural experiment" to validate Sandia's shock physics codes, CTH and PCTH, for an impact involving velocities, masses, and kinetic energies many orders of magnitude higher than had ever before been witnessed. By simulating a natural astronomical event, the validation could be based on observational, rather than on experimental data. Additional reasons for our work were to provide predictions to help guide astronomical observations of the event (see pre-impact prediction papers, 1-3), and to assist astronomers in interpreting the observational data (4-5). More recently, we have added another objective: to apply the lessons learned from this event to issues of national and economic security. In this paper we briefly describe our interpretation of observations of the SL9 impact plumes, and present a preliminary analysis of the implications of a much smaller impact event on Earth. Details of all our calculations can be found in the papers listed in references section.

OBSERVATIONS ON JUPITER

Figure 1 presents a side-by-side comparison of a 3-D simulation of plume evolution following the impact of a 3 km diameter ice fragment with a sequence of images collected by the Hubble Space Telescope during the impact of one of the largest fragments (6). In this simulation, the plume reaches an altitude nearly twice that observed for several plumes observed by Hubble, suggesting that the actual diameter of the fragments (or swarms of particles) was somewhat smaller than 3 km at the time of entry into Jupiter's atmosphere.

The geometry and timing of the series of impacts could hardly have been better for making useful observations from Earth. With the impact location only a few degrees beyond Jupiter's limb, (horizon) the hot debris (fireball) ejected by each collision had to rise only a few hundred kilometers to become visible. It could then be seen in profile, making it possible to observe its shape and size. The vantage point from Earth was close to perpendicular to the trajectory of the fragments, so that the effect of impact obliquity could be seen. Because the impact point was beyond the limb, the time of arrival of debris above the line-of-sight altitude could be measured. Combining this information with the time of impact extracted from direct measurements from Galileo (and in some cases from Earth), the fireball trajectory can be determined. The position of Jupiter (near quadrature) put the luminous debris in shadow when it first rose into view, making it possible to determine its brightness. This configuration also means that additional trajectory information can, in principle, come from the time of arrival of the fireball into sunlight, as it is condensing and evolving into a high plume. Morphology information can be extracted from the shadow-line on the plume. Furthermore, each impact site was on the side of Jupiter (near local dawn) that immediately rotated into view from Earth, giving the fireball a velocity component toward the limb, and making it possible to observe the pattern of debris and wave phenomena immediately after impact (see discussion in 4). This best-case impact configuration allows many direct comparisons to be made between simulations and observations.

IMPLICATIONS FOR EARTH

Figure 2 suggests that the physics of atmospheric entry and plume generation is similar over many orders of magnitude in the scale of impactor kinetic energy and physical size. The figure makes a direct comparison between the Crawford et al. (5) 3-D fireball simulation and an eyewitness artist's depiction of the February 12, 1947 Sikhote-Alin fireball in Siberia. The Sikhote-Alin impact energy was 10-20 kilotons, whereas the simulated fireball is from a 6 million megaton impact event, nearly a billion times as energetic.

The series of impacts on Jupiter has shown that ballistic impact fireballs and plumes are ejected to very high altitudes, and that explosive expansion of shocked atmosphere along the entry column is highly directional and poorly modeled by point explosions. These observations lead to the suggestion that satellites in low-Earth orbit (LEO) may be vulnerable to ejection of material into their environment by an impact into the atmosphere. Because of the high orbital velocities of these satellites (about 7 km/s), even a very low-density plume ejected into their path would be catastrophic.

To test this idea, we have performed preliminary 2-D simulations of the plume generated by a 34-m diameter stone (density=3 g/cm^3) impacting at 20 km/s with vertical incidence. The kinetic energy of the impactor is equivalent to an explosive yield of 3 megatons of TNT, and the expected frequency of such an event is about once per century (7). The details of this calculation are given by Boslough and Crawford (8). For comparison, the evolution of the buoyant fireball generated by a point-source explosion of the same magnitude is shown.

This preliminary analysis suggest that satellites at low altitude are indeed at risk from plumes due to impacts as small as a few megatons. This newly-recognized threat should be examined by further modeling and by extensive observational validation by gathering data on the continuous impact flux of smaller objects.

ACKNOWLEDGMENTS

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000, and funded by the LDRD program.

REFERENCES

1. Boslough, M.B., et al., *Geophys. Res. Lett.* **21**, 1555-1558, (1994).
2. Boslough, M.B., et al., *Eos* **75**, 305-310, (1994).
3. Crawford, D.A., et al., *Shock Waves* **4**, 47-50, (1994).
4. Boslough, M.B., et al. *Geophys. Res. Lett.* **22**, 1821-1824, (1995).
5. Crawford, D.A., et al., *Int. J. Impact. Engng.*, in press, (1995).
6. Hammel, H.B., et al., *Science* **267**, 1288-1296, (1995).
7. Morrison, D., et al., in *Hazards Due to Comets & Asteroids*, T. Gehrels, editor, 59-91 (1994).
8. Boslough, M.B., and Crawford, D.A., *Procs. Planetary Defense Conf.*, in press (1995).

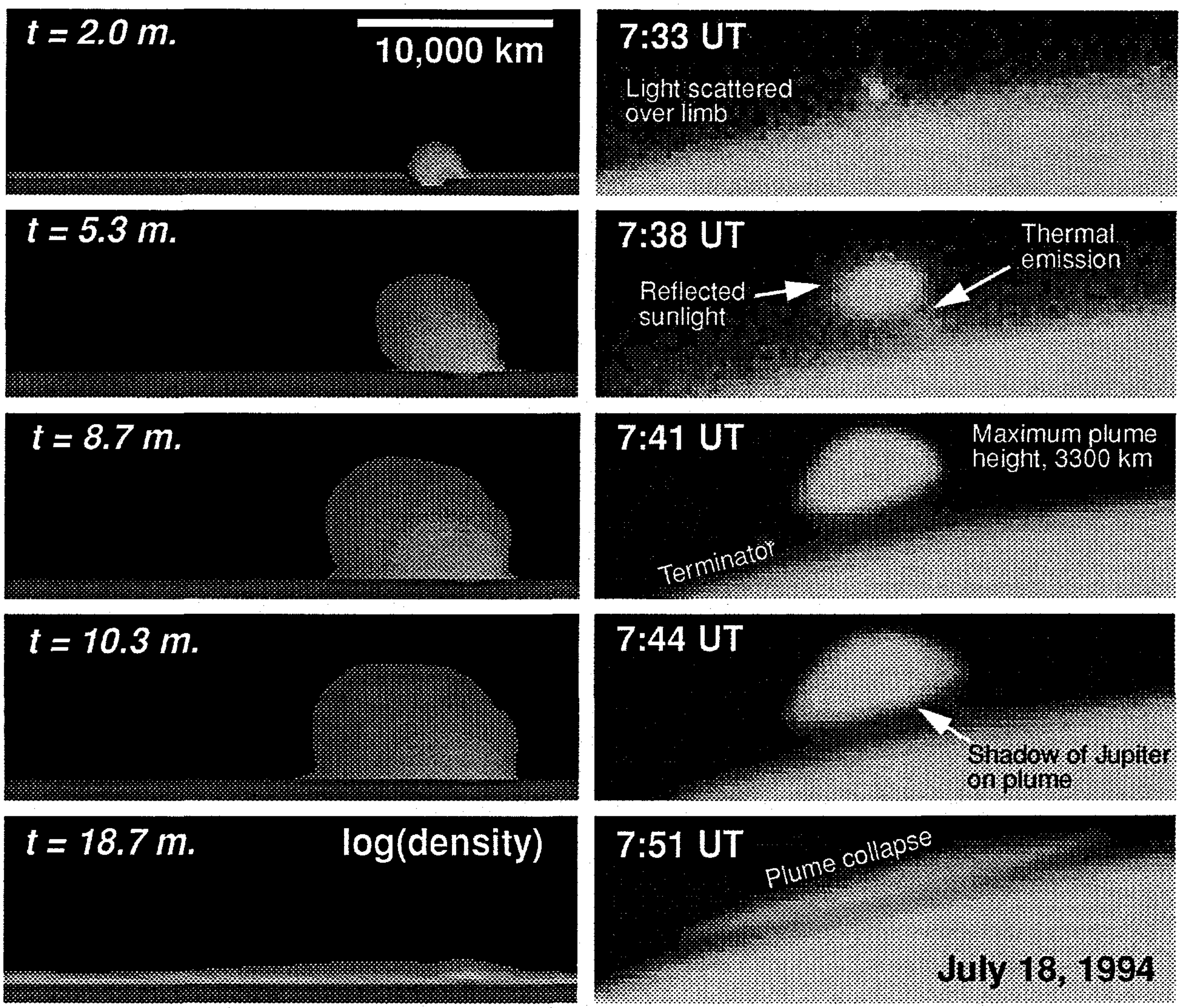

FIGURE 1. Left: Simulation of 3-D fireball/plume evolution after the impact of a 3-km diameter fragment. Shading indicates log(density) with a cutoff at 10^{-12} g/cm3; times are in minutes after impact. Right: Sequence of G plume images collected by Hubble Space Telescope (6).

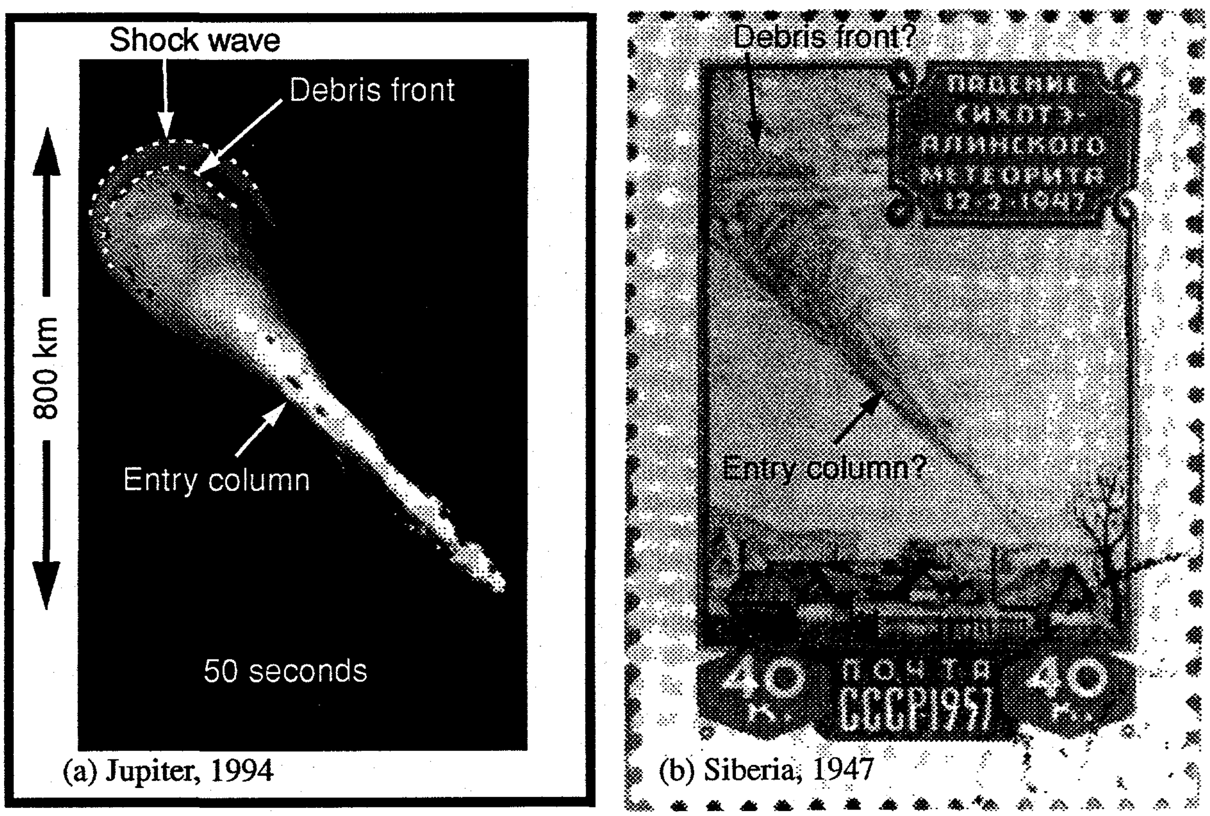

FIGURE 2. Comparison of (a) 3-D simulation of impact of 3-km diameter fragment on Jupiter, 50 seconds after entry (Crawford et al., 5) with (b) artist's depiction of 1947 Sikhote-Alin impact.

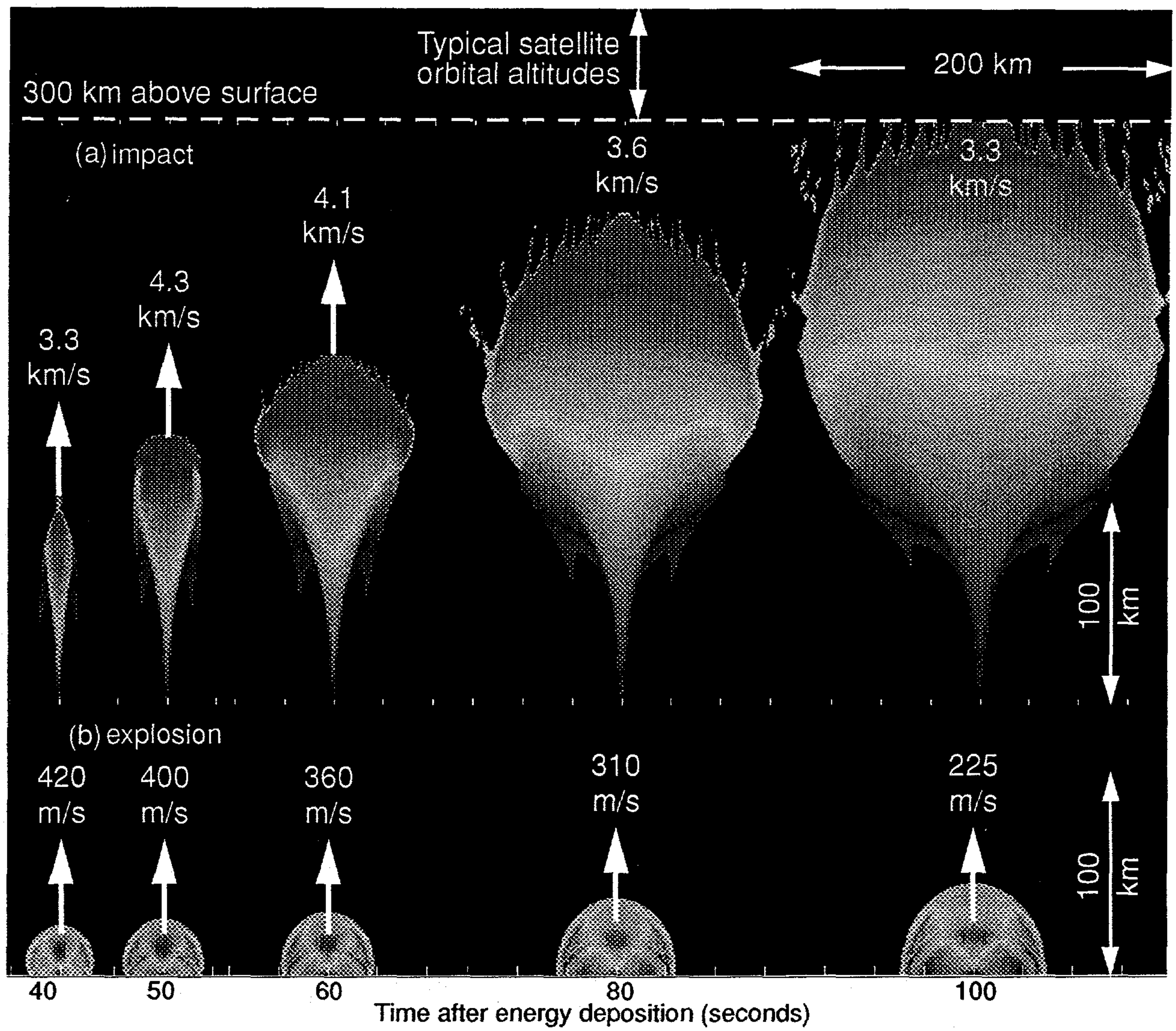

FIGURE 3. Comparison on the same scale of evolution of (a) ballistic fireball generated by 3 megaton impact to (b) buoyant fireball generated by a 3 megaton explosion at same altitude of maximum energy deposition (7 km). Shading indicates velocity magnitude of the air.