Analysis of the Marshall Islands Fireball of February 1, 1994

E. Tagliaferri
E T Space Systems

R. Spalding
Sandia National Laboratories

C. Jacobs
Sandia National Laboratories

and

Z. Ceplecha
Ondřejov Observatory

Abstract. See section "Conclusions".

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1 Introduction

On February 1, 1994, at 22:38 UTC a massive meteoroid impacted over the Pacific Ocean at 2.6° N, 164.1° E, about 300 km south of the Island State of Kosrae, Micronesia. The impact was observed by space based infrared (IR) sensors operated by the US Department of Defense (DOD), and by visible wavelength sensors operated by the US Department of Energy (DOE). The energy radiated in the visible by the fireball was approximately 1.3×10^{13} joules. The entry velocity of the object was approximately 24–25 km/sec. These observations result in estimates for the mass of the body of between 1.6×10^5 kg and 4.4×10^6 kg, and diameters ranging from 4.4 to 13.5 meters.

The fireball was also reported by two men who were fishing off the coast of Kosrae at the time. Interestingly, one of the men reported hearing a "whooshing" sound, turned and saw the object. By the time he called to his partner, the object had passed from sight. However, the trail was still visible, and remained visible for up to an hour after the impact. In spite of being over 300 km from the impact site, the men described the event as "awesome and frightening". They did not report hearing any explosions or sonic booms.

The DOD IR sensors have regularly detected impacts of meteoroids in the atmosphere over the past twenty years, but the data have remained within the defense community until recently (Tagliaferri et al., 1994; McCord et al., 1994). Changes to the DOE visible wavelength sensor suite in recent years have added the capability of observing impacts in the visible as well.

In this paper we discuss the satellite observations, but of necessity will not be able to discuss details of the satellites or the sensors themselves. Nevertheless, we feel that the data represent a valuable addition to the science community, and can

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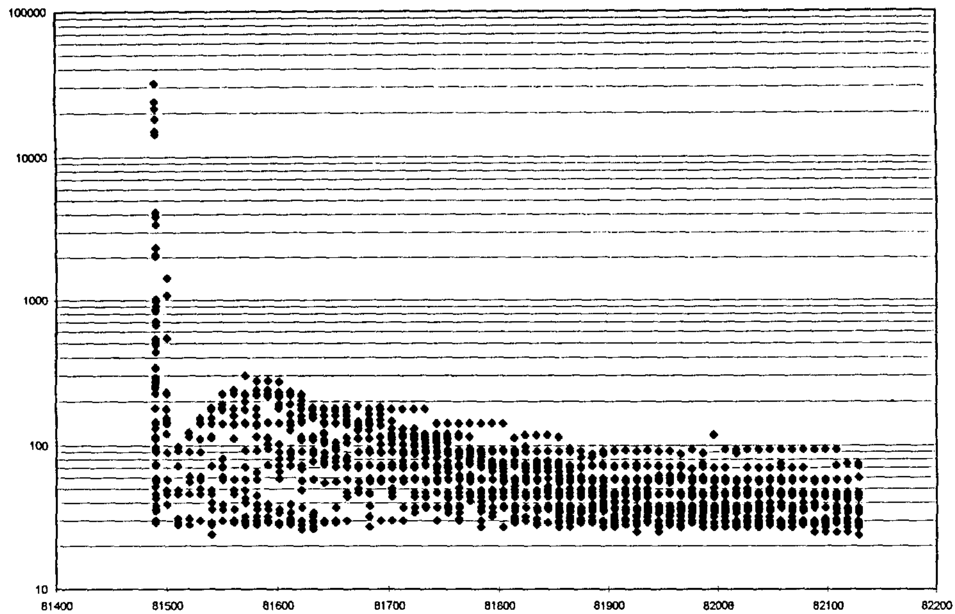

Fig. 1. Intensity (KW/ster) vs time (seconds) of the February 1, 1994 bolide from the short wavelength infrared sensor aboard a DOD satellite. (Sensor 1).

significantly improve our knowledge of the flux of moderately sized objects (about 10 meters diameter or so) in the vicinity of the Earth.

2 Observations

The object under discussion was first detected at about 54 km altitude. It either was in pieces before it entered the atmosphere or else it broke into pieces as it entered. In either case, as it progressed downward, several pieces are detectable in the IR signature. One large piece underwent explosive disintegration (which I will refer to as a "detonation" in this paper) at about 34 km at 2.61° N, 164.14° E, and a second, larger piece detonated at about 21 km altitude at 2.66° N, 164.05° E. Fig. 1 presents the response from IR sensor number 1. Shown is the intensity (in kilowatts per steradian), vs time (GMT in seconds after midnight). What we see first in Fig. 1 is a high intensity spike of radiation from the fireball, followed by a rapid decrease in intensity as the fireball cools. Because of the intensity of the fireball the sensor is saturated, making it difficult to accurately place a number on the true value of the peak intensity, but the true intensity is probably 8 to 10 times that shown.

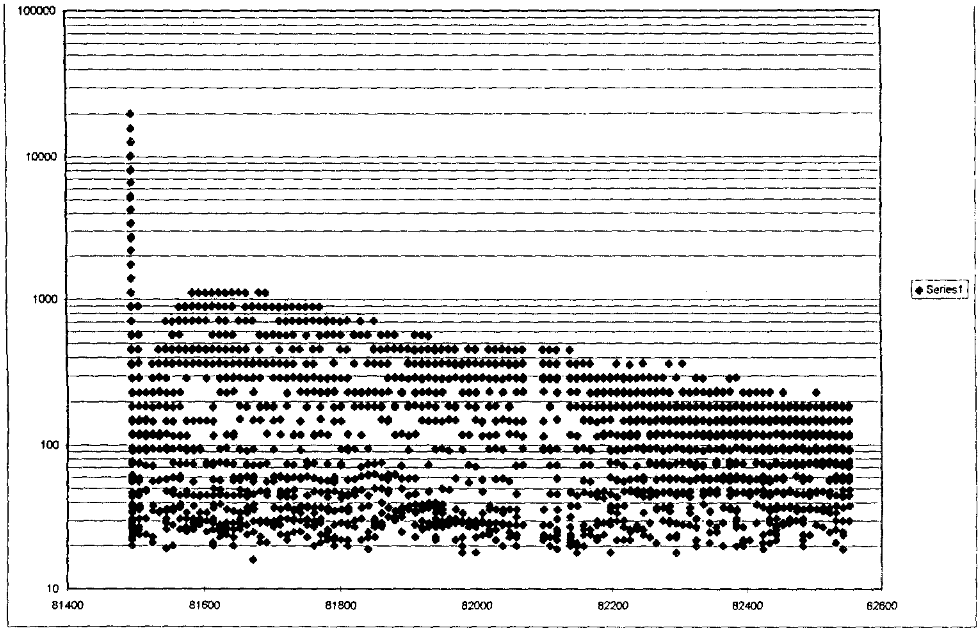

Fig. 2. Intensity (KW/ster) vs time (seconds) of the February 1, 1994 bolide from the short wavelength infrared sensor aboard a DOD satellite. (Sensor 2).

The decrease in intensity after the initial burst of energy is followed by a slow rise in intensity, which results from sunglint off the debris cloud that remains after the detonation of the object. The debris cloud is then tracked as it expands and drifts due to the action of high altitude winds. The debris cloud persisted for over an hour; what is shown in the figure is about the first 12 minutes of data.

Sensor 1 scans the event first, and in fact scans just after the first piece of the object detonates (at about 34 km altitude), but about half a second before the second, much larger, piece detonates (at about 21 km altitude).

Fig. 2 shows the response from IR sensor number 2. Again we have plotted intensity (in kW/ster) vs time (in seconds). Again, we see the initial burst of energy from the fireball, followed by a rapid decrease in intensity as the fireball cools. We then see the intensity slowly rise again due to sunglint off the debris cloud. In this case the sensor scans the area after the detonation of the second piece at 21 km altitude has occurred.

It is particularly interesting to look at the spatial distribution of IR returns. Fig. 3 presents the returns from sensor 1. The data are plotted in sensor azimuth/elevation space, which can be mapped into latitude/longitude. Presented this way, one can see the track of the object, and the formation and drift of the debris cloud.

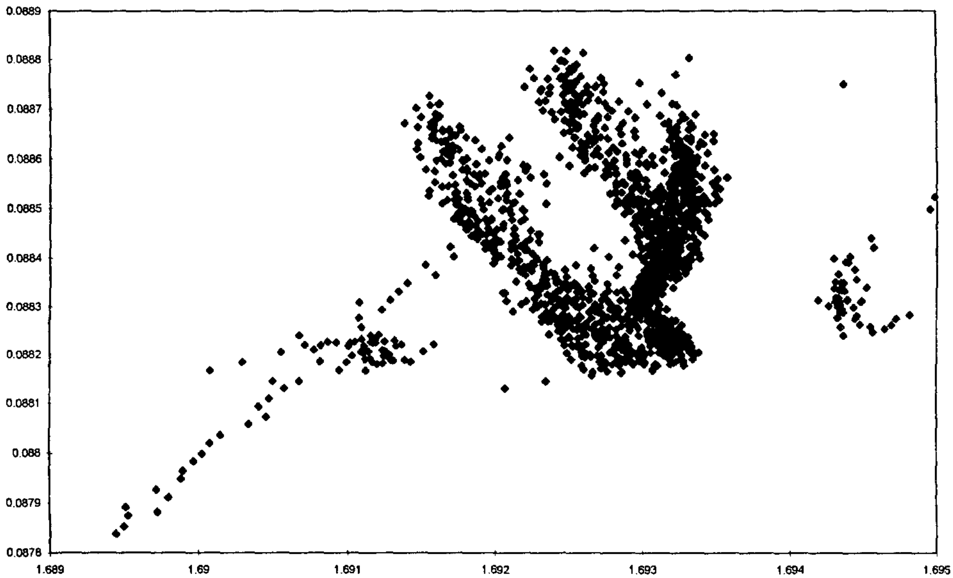

Fig. 3. Spatial distribution of IR returns of bolide of February 1, 1994. Data are plotted in sensor azimuth/elevation space (which maps into latitude/longitude).(Sensor 1).

In Fig. 3 the straight line of A's appearing on a diagonal (from upper right to lower left) do not belong to the track of the object, but is an artifact. The track of the object goes from left to right at an elevation of 0.0882. It is possible to resolve the cloud from the first (high altitude) detonation at about elevation 0.0882/azimuth 1.691, and the cloud from the large second piece at about the same elevation and azimuth 1.693. There may be a third detonation (albeit much smaller) at elevation 0.0883 and azimuth 1.695, but it has not been possible to unambiguously separate it out yet. It may also be that the large "piece" that detonates at 21 km is really two pieces that detonate 3 or 4 km apart in altitude (one on either side of azimuth 1.693).

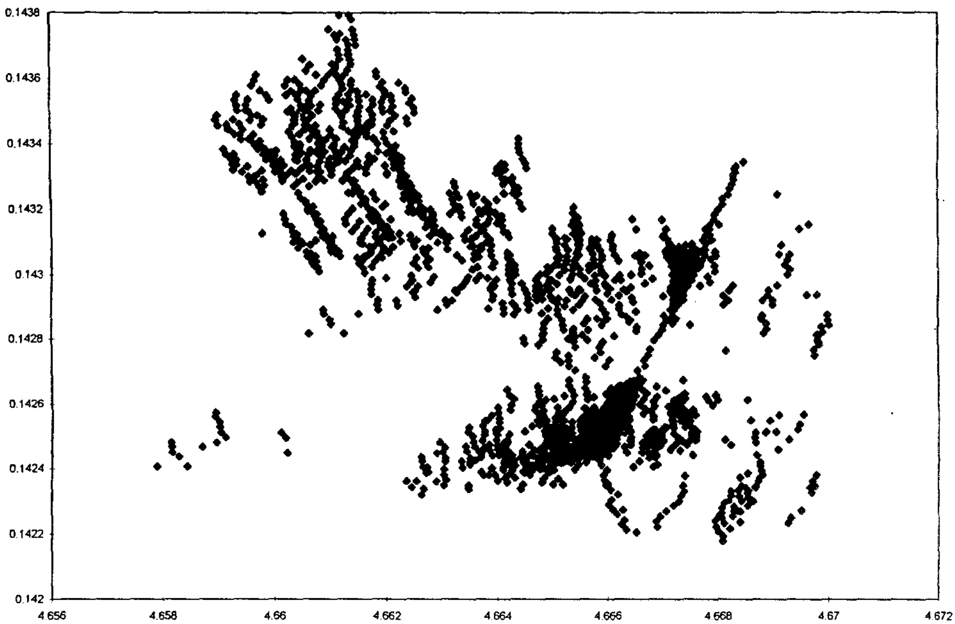

Fig. 4. Spatial distribution of IR returns of bolide of February 1, 1994. Data are plotted in sensor azimuth/elevation space (which maps into latitude/longitude).(Sensor 2).

Fig.4 presents the spatial distribution of returns from IR sensor 2. In this case the line of A's going from upper right to lower left is the track of the object. The detonation of the smaller piece appears at about elevation of 0.143/azimuth of about 4.6675, and the detonation of the larger (low altitude) piece at an elevation of about 0.1425/azimuth 4.666. Again, it is possible that the detonation of the large "piece" is accompanied by other pieces detonating in the vicinity (for example, to the right of the main fireball), but at this time it has not been possible to unambiguously separate them out.

Fig. 5 presents a visible wavelength light curve assembled from the response of several DOE sensors. Using this light curve, it is possible to estimate the energy released in the detonations. The integrated area under the curve is approximately 1.4×10^{13} joules; assuming a 6000 K black body and a 30 % efficiency for the conversion of the kinetic energy of the body to visible light, we estimate the energy of the original object to be about 4.6×10^{13} joules, or about 11 Kilotons of TNT. From a second set of DOE sensors, it was possible to estimate a velocity for the object of approximately 25 km/sec at 34 km altitude, and about 23 km/sec at 21 km altitude. The estimate of a 6000 K black body may not be correct for the effective temperature of the fireball, but it is the apparent temperature of the

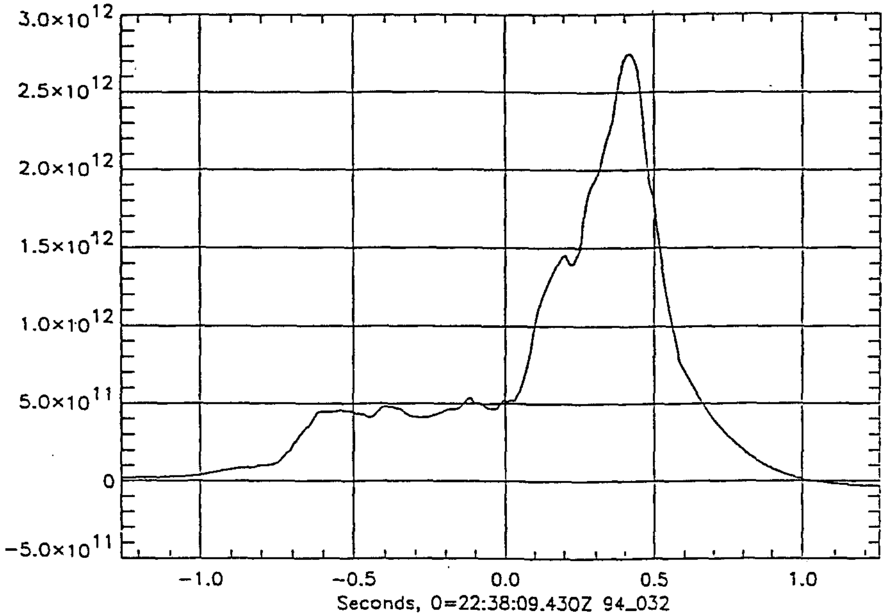

Fig. 5. Visible wavelength light curve of the February 1, 1994 bolide. Shown is the intensity (Watts/ster) vs time (seconds). The plot is a composite of data from several different silicon detectors.

fireballs of atmospheric nuclear detonations, and we have been unable to obtain a more defensible number. The conversion efficiency of 30 % is certainly not correct, but again we find, in the literature and from private communications with practitioners in this area, such a large range of values for this number that we leave it to the reader to put in their favorite number and derive their own estimate of the kinetic energy of the object.

3 Results

Given the altitude and locations of the detonations of the two pieces, it is possible to reproduce the trajectory of the meteoroid. This is presented in Fig. 6. As can be seen, we make the object as entering at a 45° angle on a heading of approximately 300°, i.e., traveling in a southeast to northwest direction.

Assuming a kinetic energy for the body of 11 KT (4.6×10^{13} joules), and a velocity of approximately 25 km/sec, the mass of the body would be about 1.6×10^5 kg. For a stony object of density of 3.5 g/cm^3, the object would be about 4.4 meters in diameter. If on the other hand the efficiency for the conversion of kinetic energy of the body into visible light is more like 1 %, as some have suggested, then

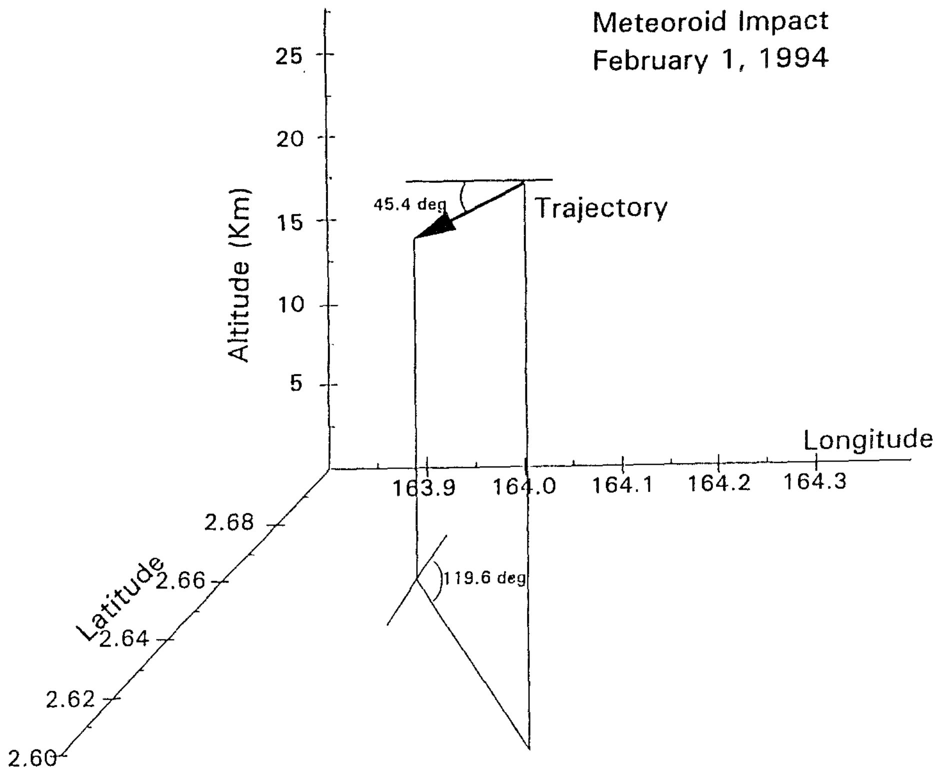

Fig. 6. Atmospheric trajectory of bolide of February 1, 1994.

the mass of the object would be 4.4×10^6 kg, and the diameter would be 13.5 meters.

4 Orbit determination

Using a gross-fragmentation model (Ceplecha et al., 1993) with 2 fragmentation points (34 km and 21 km altitude), and the results of the satellite observations, light curves were computed for bodies of different sizes and compositions. Average values of the density and ablation coefficients used were based on photographic observations of meteoroids ranging from cm up to meter sizes (Ceplecha, 1988). Different assumptions were made for the initial size of the body, the relative mass depletion of the body at the fragmentation points, and the luminous efficiencies (i.e. the efficiency with which the kinetic energy of the body is converted into visible light).

Fig. 7 presents a summary of several light curves for various types and compositions of the initial body. The best fit appears to be for a stony body of between

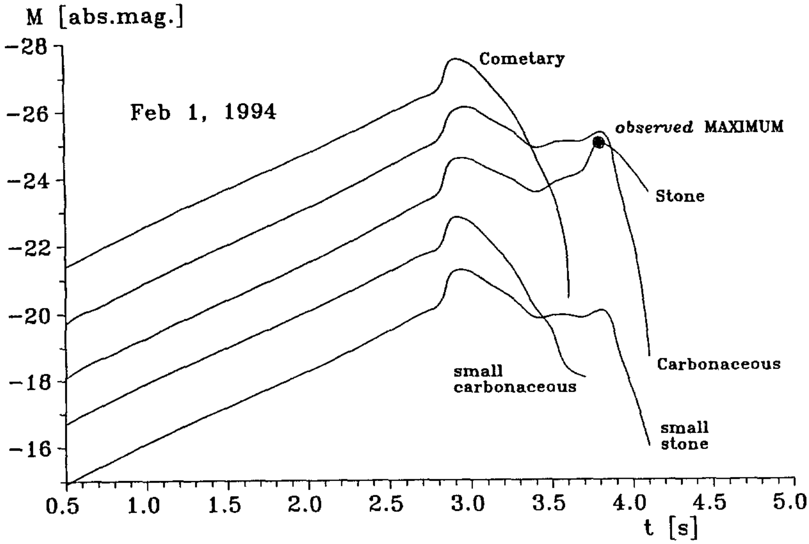

Fig. 7. Light curves generated using a gross-fragmentation model and data from satellite observations. The point labeled 'observed MAXIMUM' is the maximum from the visible wavelength satellite data.

TABLE I

Orbital characteristics of the parent body of the Marshall Islands Fireball of February 1, 1994, computed for two different values of initial velocities. α_R, δ_R ... right ascension and declination of the observed radiant, α_G, δ_G ... right ascension and declination of the geocentric radiant, v_∞ ... initial velocity, v_G ... geocentric velocity, $a, e, q, Q, \omega, \Omega, i$ ... orbital elements (2000.0).

α_R deg	δ_R deg	v_∞ km/s	α_G deg	δ_G deg	v_G km/s	a AU	e	q AU	Q AU	ω deg	Ω deg	i deg
313	−19	22.9	315	−20	19.7	1.73	0.66	0.59	2.9	269	132.921	2
313	−19	25.0	315	−20	22.1	2.10	0.74	0.56	3.7	268	132.921	2

10 and 20 meters diameter, which is in agreement with the results obtained from the satellite data alone.

Table I presents the orbital parameters derived for the body prior to impact. Fig. 8 presents a pictorial schematic of the orbit.

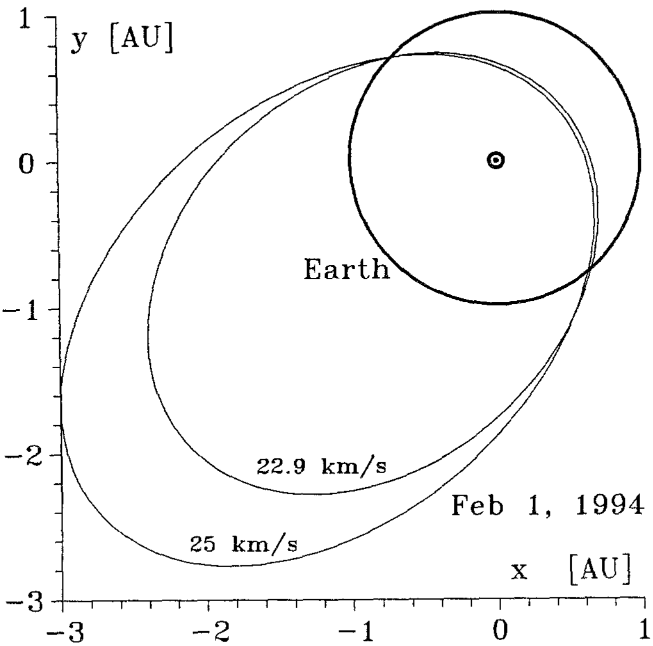

Fig. 8. Schematic representation of the orbit of the parent body of the Marshall Islands Fireball of February 1, 1994, on assumption of two different initial velocities, 22.9 and 25.0 km/s.

5 Conclusions

On February 1, 1994, a large meteoroid impacted over the Pacific Ocean at 2.6° N, 164.1° E. The impact was observed by space based IR sensors operated by the US Department of Defense and by visible wavelength sensors operated by the US Department of Energy. During entry the object broke into several pieces, one of which detonated at 34 km and another at 21 km altitude. The entry velocity of the object is estimated to be 24 – 25 km/sec. Based on the visible wavelength data, the integrated intensity of the radiated energy of the fireball was approximately 1.3×10^{13} joules. Assuming a 6000 K black body and a 30 % efficiency for the conversion of the kinetic energy of the body into visible light, we estimate the mass of the body to be between 1.6×10^5 kg and 4.4×10^6 kg, and to have a diameter of between 4.4 and 13.5 meters. The object entered at a 45° angle, traveling on a heading of approximately 300°, i.e. from the southeast to the northwest. Calculations using a gross-fragmentation model indicate that the body was most likely a stony object larger than 10 m with an Apollo orbit prior to impact.

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