11. Energy of Impact ❖ ❖ ❖

The kinetic energy of an impacting asteroid is one-half its mass times velocity squared. As discussed in the previous chapter, the projectile is usually assumed to have a pre-collisional diameter of roughly 10 to 50 m, which represents a mass of ~4,000 to 500,000 metric tons (Table 9.2.). The impact velocity is usually assumed to be between 11 and 20 km/s.

Those dimensions and velocities reflect a wide range of impact energy. Published estimates range from an impact energy equivalent to a few tens of kilotons of TNT to over 60 megatons of TNT (Table 11.1). When Shoemaker (1960, 1963) published his classic study of the crater and analogies with nuclear explosion craters, he estimated an impact energy equivalent to ~1.4 to 1.8 MT. This estimate was based on a cube-root scaling law that he calibrated with the Teapot Ess nuclear explosion. Schmidt (1980) conducted centrifuge experiments, from which he derived a new set of scaling laws. Based on those results, he suggested much higher impact energies, ranging from 22 to 61 MT. At nearly the same time, Roddy *et al.* (1980) developed a new computer model of crater excavation and estimated a 15 MT blast for a vertical impact. Shoemaker (1987) concluded the energy was probably a little higher than 15 MT, because the impact was more likely to have had an oblique trajectory. Roddy and Shoemaker (1995) revised their computer simulations and suggested 20 to 40 MT is a better estimate, which is a rough average of Shoemaker's original estimate and Schmidt's estimates. Unfortunately, the details of those computer simulations only appeared in preliminary form and the details are now lost.

More recently, a family of estimates have been appearing that are dramatically lower and approach Shoemaker's original estimate of the impact energy. These calculations have been emphasizing three features of the impact process: atmospheric deceleration, disruption, and ablation. Before discussing the new results, it may be useful to digress a moment to discuss atmospheric deceleration, disruption, and ablation.

With regard to atmospheric deceleration, it may be best to begin with small isolated iron meteorites. These objects fall to Earth with the same range of velocities as larger, Canyon Diablo-size asteroids, when they first encounter the top of the atmosphere. These small objects are, however, completely decelerated in the atmosphere and eventually fall with a velocity governed by Earth's gravity. Larger impacting bodies with masses substantially greater than the mass of atmosphere they encounter will not be significantly decelerated and will then hit the Earth's surface with most of their cosmic velocity intact. The Canyon Diablo asteroid is at the small end of the range that produces impact craters, so it may represent an intermediate case. It may have been partially decelerated, but still able to maintain enough motion to generate a hypervelocity impact crater.

The Canyon Diablo asteroid is also at the small end of the range of objects that produce impact craters, as discussed briefly in Chapter 9. Smaller objects and weaker objects often catastrophically fragment in the atmosphere. A nearby example is the 6 to 8 m Gold Basin brecciated stony meteoroid that failed to reach the ground intact in northwestern Arizona (Kring *et al.*, 2001). More recent examples are the Tunguska and Chelyabinsk impact blasts (*e.g.*, see Kring and Boslough, 2014, for a popular science summary), in which stony impactors catastrophically fragmented above Russia. None of those events produced a hypervelocity impact crater. Potentially, the Canyon Diablo asteroid began to fragment, but not catastrophically, and reached the ground with a sufficiently large main mass or with a sufficiently dense cluster, while maintaining a significant fraction of its cosmic velocity.

When meteoritic material enters the atmosphere, surfaces are heated dramatically, melt, and slough off. They are ablated. Radiating flow lines generated in the melt are often preserved in meteoritic fusion crusts. Because this is a surface phenomenon, the effect is usually proportionally smaller for larger objects that have larger volume to surface area ratios. However, if a larger object begins to fragment and greatly enlarge the amount of surface area, ablation may consume an increasingly large fraction of the original asteroid.

Calculations that explicitly examine atmospheric deceleration, disruption, and ablation processes are generating new estimates of the impact energy that fall in the range of ~1 to 10 MT (Melosh and Collins, 2005; Artemieva, 2006). Because the asteroid is being decelerated, a larger mass and diameter for the original asteroid are implied. For example, Artemieva (2006) calculates a ~40 m diameter coherent iron asteroid with an 18 km/s collisional velocity has sufficient energy to create the crater. However, if she allows for disruption and ablation, she requires a 57 m diameter asteroid that was decelerated to a final impact velocity of 11 km/s or a 46 m diameter asteroid that was decelerated to a final impact velocity of 15 km/s. Both generate about 10 to 11 MT, which her calculations suggest is sufficient to excavate the crater and fracture the surrounding wall rock. That model continued to evolve (Artemieva and Pierazzo, 2009, 2011) and produced energies of 7 to 15 MT. A more recent numerical model that fit crater morphometry, structural deformation, and the crater's gravity signature (Collins *et al*., 2016) produced required an energy of 8.6 MT. Thus, the numerical models appear to be converging on surface impact energies of nearly 10 MT, with initial energies at the top of the atmosphere about 50% greater.

Table 11.1. Estimates of Impact Energy

Energy (MT TNT equivalent)	Source
38.8	Magie 1910 (per Hoyt 1987)
38	Moulton (per Hoyt 1987)
2.91	Moulton (per Hoyt 1987)
0.21	Wylie 1943 (per Hoyt 1987)
0.08	Baldwin 1949 (per Hoyt 1987)
4.8	Gilvarry and Hill 1956 (per Hoyt 1987)
64	Opik 1958 (per Hoyt 1987)
1.4 to 1.8	Shoemaker 1963
8.1	Baldwin 1963
4 to 5	Shoemaker 1974
22 to 61	Schmidt 1980
15	Roddy *et al.* 1980
15+	Shoemaker 1987
20 to 40	Roddy and Shoemaker 1995
5.3	Schnabel *et al*. 1999 (calc. for their 15 m radius & 20 km/s velocity)
0.44	Ai and Ahrens 2004 (calc. for their 9 m diameter & 33 km/s velocity)
2.5	Melosh and Collins 2005
10 to 11	Artemieva 2006 (calc. for her 46-57 m diameter & 15-11 km/s velocity)
7 to 15	Artemieva and Pierazzo 2009 (calc. for their 46-66 m diameter & 15-18 km/s velocity)
8 to 12	Artemieva and Pierazzo 2011 (calc. for their 40-47 m effective diameter & 16 km/s velocity)
8.6	Collins *et al*. 2016 (calc. for their 3.2×10^8 kg, 42 m diameter projectile, & 15 km/s velocity)

For cases where kinetic energy is calculated from authors' estimates of projectile size and velocity, I assume a projectile density of 7.8 g/cm^3. For the effective diameter of Artemieva and Pierazzo (2011), I used the effective density that they tabulated. Please note there was a typographical error in Collins *et al*. (2016), so the mass was reported at 10^8 kg rather than 3.2×10^8 kg.