A METEORITE PERSPECTIVE ON PLANETARY DEFENSE. Derek W.G. Sears[1,2], Timothy J. Lee[1], Jesse Dotson[1], Megan Bruck Syal[3], Damian C Swift[3]. [1]NASA Ames Research Center (ARC), Moffett Field, CA, U.S.A., [2]BAER Institute, Ames Research Center, Moffett Field, CA, U.S.A. [3]Lawrence Livermore National Laboratory (LLNL), 7000 East Avenue, Livermore, CA 94550.

Introduction: Following the fall of the Chelyabinsk meteorite [1,2], and programs to detect hazardous asteroids and mitigate their threat to Earth [3,4], we have established a team and are developing laboratories at the ARC and LLNL designed to provide the information required to understand (1) the physics of meteorite fall and (2) the details of asteroid surfaces needed to develop deflection techniques. Here we review our thoughts on what can be learned about planetary defense from meteorites and meteorite falls.

I. The Mechanics of Meteorite Falls.

Observed Falls: While subjective in nature, eye witness observations of meteorite falls have the potential to provide unique insights into the physics of entry into the Earth's atmosphere (Fig. 1). A limited but suggestive study [5] demonstrates the potential of reviewing large numbers of literature fall descriptions (Table 1). Witnesses can also indicate the amount of dust associated with a fall which, in turn, provides information on the amount of fragmentation and ablation (Fig. 2, [6]).

Table. 1. Fall descriptions of 20 meteorites in the Meteoritical Bulletin (Apr 1960 – Nov 1970) [5].

Feature	No.	%
Explosion	17	85
Rumbling	7	35
Whistling	9	45
Impact sounds	4	20
Light	11	55
Flares	2	10
Dust trail	6	30

Fig. 1. The Sutter's Mill meteorite, like Chelyabinsk, is an example of a recent meteorite fall that was well observed and even photographed so its fall behavior is well understood [7].

Light Curves: Until the early 1990s it took expensive networks to obtain light curves for fireballs (Fig. 3). Since the development of private video equipment, nearly 20 meteorite falls have been recorded and light curves obtained [e.g. 8]. Light curves enable quantitative information on the beginning and end of luminous flight, the rate of energy loss, the dynamic and photometric mass, major break-up events, and velocity as a function of time. More importantly, the light curve is quantitative data that can be used to test numerical models.

Fig. 2. Chelyabinsk is an example of a meteorite that produced considerable dust reflecting its high rate of fragmentation and ablation.

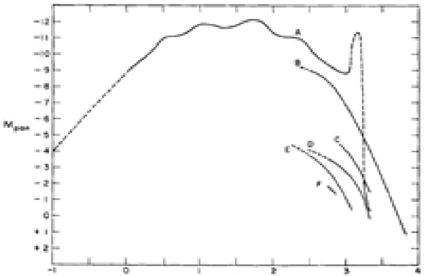

Fig. 3. Light curve for the Innisfree meteorite [9]. The slow rise and sudden drop, oscilations, and flares, provide information that can be numerically modeled.

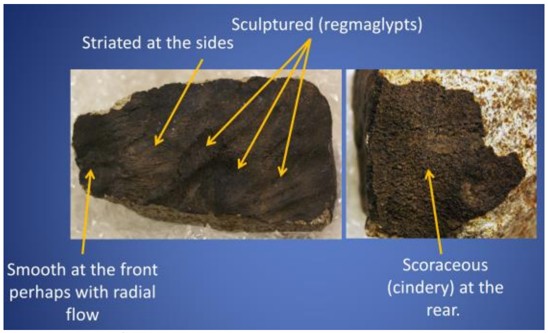

Fig. 4. The fusion crust enables insights into the later stages of atmospheric flight, including air flow, thermal gradients, and ablation rates [11].

Fusion Crust and Shape: The fusion crust is an eye witness of the later stages of flight (Fig. 4). From its surface texture, details of airflow around the meteorite can be determined, and from the petrography of the fusion crust and underlying layers, thermal gradiatents and ablation rates can be determined [5,10,11]. From the shape and coverage by fusion crust, the degree of orientation, can be determined.

Table 2. Craters with meteorites [12]

Crater	Meteorite		
Wabar	Iron (IIIAB)	Macha	Iron (Iron)
Kaalijarvi	Iron (IAB)	Monturaqui	Iron (IAB)
Henbury	Iron (IIIAB)	Wolf Creek	Iron (IIIAB)
Odessa	Iron (IIIAB)	Meteor	Iron (IAB)
Boxhole	Iron (IIIAB)	Rio Cuarto	H Chondrite

Meteorite Fragments from Craters: Of the 10 meteorite impact craters from which meteorites have been recovered, nine were iron meteorites (Table 2). The exception is the largest crater which was produced by an H chondrite [12]. Here we have a unique opportunity to test numerical models because we have two pieces of critical data, the crater and the meteorite.

II. Details Fall and Asteroid Surfaces

Meteorite characterization not only aids in modelling atmospheric behavior, it also has the potental to provide insights into the asteroid surfaces.

Laboratory Studies of Meteorites: Of course, since we have the meteorites in our laboratories any number of relevant measurements can be made.

Table 3. Mass loss for meteorites during atmospheric passage estimated from cosmogenic isotopes* [5].

Meteorite	(%)	Meteorite	(%)
Abee	37, 51	Ochansk	0,0,0
Akaba	99	Parnallee	95, 99
Beenham	78	Ramsdorf	99, 99
Colby, Wisc	24	Saline	92.2
Dimmitt	96.5	St. Germain	87
Finney	95	St. Severin	0, 32
Kiel	80	Texline	95.8
Ladder Creek	94.2	Tieschitz	86
Leedey	87.5	Tynes Island	96.7
Maziba	95	Utzenstorf	93.2
Mezo Madaras	98.4, 94.2	Walters	97.2, 95.3
Mocs	40, 70, 99.7	Pulsora	99, 99
Narellan	96	Ramsdorf	99
Ness City	98.3	Saline	92.2
Norton County	56	Weston	75, 81

* Multiple entries means multiple estimates.

Chemical properties. Samples in the laboratory can be subjected to a vast array of analyses, starting with those required for classification.

Physical Properties. Essential properties such as density, porosity, thermal conductivity, heat capacity, acoustic properties, and tensile, compressive, and deformation strength, albedo and spectra, can be measured accurately [13-15]. Additionally we will perform laser-driven shock experiments to measure flow stress, phase transition pressure, and tensile (spall) strength, and microindenter experiments to measure temperature-dependent strength at lower strain rates.

Preatmospheric Size. Studies of cosmogenic isotopes can be used to calculate preatmospheric mass. For example, Table 3 suggests that while most meteorites suffer >98% mass loss in coming through the atmosphere, 25% show relatively little mass loss.

Internal Structure. Meteorites of the same chemical class can have very different internal properties that can greately influence atmospheric behavior (Fig. 5).

Fig. 5. Internal structure critically affects atmospheric behavior. Above are chemically similar meteorites, one was made extremely weak (Chelyabinsk, left) and one was made extremely tough (Novato, right) by impact events in space.

III. Asteroid surfaces

Regolith Breccias: The gas-rich regolith breccias (with characteristic light-dark texture) are samples from the very surface of their parent asteroids and provide unique information on the surface of asteroids (Fig. 6, [16]).

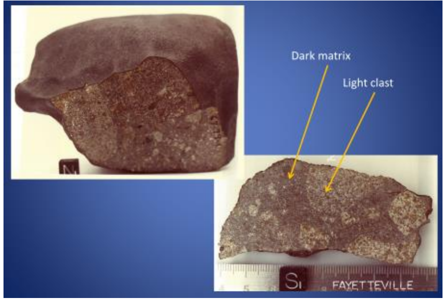

Fig. 6. The Fayetteville gas-rich regolith breccia.

Conclusion: Meteorite studies constitute an integral part of the Nation's planetary defense efforts alongside NEA characterization, numerical studies of reentry, risk analysis, and deflection techniques.

References/Notes: [1] Popova et al. 2013. Science 342, 1069. [2] Brown et al 2013. Nature 503, 238. [3] Gehrels 1994. "Hazards due to Comets and Asteroids". [4] Belton et al. 2004. "Mitigation of Hazardous Comets and Asteroids". [5] Sears, 1974. PhD Thesis. [6] Carr, 1970. GCA 6, 689. [7] Jenniskens et al. 2012. Science 338, 1587. [8] Popova et al 2010. MAPS 46, 1525. [9] Halliday et al 1981. JRAS Canada 75, 247. [10] Sears and Mills 1973. Nature Physical Science 242, 25. [11] Sears 1978. "Nature and Origin of Meteorites". [12] Koeberl 1998. In "Geol. Soc. Lond. Spec. Pub. 140", 133. [13] Wood 1963. In "Moon, Meteorites, and Comets". [14] Britt and Consolmagno 2003. MAPS 38, 1161. [15] Consolmagno et al. 2013. PSS 87, 146. [16] Goswami et al. 1984. SSR 37, 111. [17] We are grateful to NASA's NEO office for supporting this work.