STRENGTHS OF METEORITES AND FRAGMENTING METEORS: IMPLICATIONS FOR STRENGTH SCALING FOR THE ASTEROIDS. G. J. Flynn[1] and D. D. Durda[2], [1]SUNY-Plattsburgh, 101 Broad St., Plattsburgh, NY, 12901 (flynngj@plattsburgh.edu), [2]Southwest Research Institute, 1050 Walnut Street Suite 300, Boulder CO 80302

Introduction: Theoretical consideration of flaw distributions [1] and observational data on rock fragmentation [2] suggest that the strength of a rocky body decreases with increasing size. It is generally assumed that the strength of an asteroid scales with mass following the statistical model proposed by Weibull [1]:

$$\sigma = \sigma_s(m_s/m)^\alpha \text{ (Equation 1)}$$

where σ and m are the effective strength and mass of the larger body, σ_s and m_s are those of a small specimen, and α is a scaling factor. In a review of literature data on terrestrial rocks Yoshinaka et al. [3] found a significant decrease in strength with mass for hard rocks, but for some soft rocks with compressive strengths <25 MPa strength did not decrease with increasing mass. The value of α is not well established for asteroids, and may vary with taxonomic type.

Slyuta [4] noted: *"There are no analogues among terrestrial igneous and sedimentary rocks and ores… [for the] set of physical and mechanical properties of the meteorites."* This suggests measurements of physical properties of meteorites, samples of asteroidal parent bodies, provide the best constraints on the properties of asteroids, including the appropriate value of α. Laboratory measurements on meteorites are generally performed on small samples, typically tens to hundreds of grams in the case of hypervelocity impacts. This results from the unavailability of large meteorite samples for destructive measurements. Thus, a knowledge of α is critical to scale results of laboratory experiments on impact disruption of meteorites and meteorite analogs to the size of asteroids and α is equally critical for inferring the size at which asteroid disruption is dominated by gravity rather than strength.

Meteorite Strength: Individual strength measurements for >35 meteorites have been reported in the literature (reviewed in Flynn et al. [5]). However, due to the limited availability of meteorites for destructive analyses, many of these measurements were conducted on a single sample of the meteorite. Since the strength varies significantly from one meteorite to another, even of the same taxoniomic type, this data provides no opportunity to examine the variation of strength with size.

There have only been a few attempts to systematically measure the variation of strength with mass for meteorites. Cotto-Figueroa et al. [6] measured the unconfined compressive strengths of ten samples, ranging from 0.96 g to 244.7 g, of the Allende CV3 carbonaceous chondrite and eleven samples, ranging 7.37 g to 100.85 g, of the Tamdakht H5 ordinary chondrite (OC). Zotkin et al. [7] measured the compressive strengths of nine samples of the Tsarev L5 OC covering a three order-of-magnitude mass range from 3.5 g to 3,500 g. These results (Figure 1) show significant variation in strength from one meteorite to another, with mean values of the strength being ~35 MPa for Allende, ~124 MPa for Tamdakht, and ~377 MPa for Tsarev. However, Figure 1 shows little variation of strength with mass for each meteorite. The least squares fit to log σ vs. log m gives negative values of α of -0.06 for Allende and -0.006 for Tamdakht, indicating a slight increase in strength with increasing mass, and a positive α value of +0.03 for Tsarev. These α values are each indistinguishable from zero, with the correlation coefficients of the best fit being r = 0.39 for Allende, r = 0.017 for Tamdakht, and r = -0.40 for Tsarev. The r^2 values indicate that a large majority of the variation in the data sets is random, with less than 20% being explained by the trend line. There is little or no variation of strength with mass over the 3.5 g to 3500 g mass range covered by these measurements.

Meteor Fragmentation Strength: Although it is generally accepted that most or all meteorites originate from asteroids, meteors sample both asteroidal and cometary sources. The Tisserand parameter with respect to Jupiter (T_J) is used to distinguish asteroidal from cometary meteors: objects with T_J >3 being asteroidal and T_J <3 being cometary. This does not provide perfect separation. Some comets like Encke have T_J >3, and modeling suggests some asteroids have T_J <3.

The dynamic pressure experienced at fragmentation is interpreted as the "fragmentation strength" for a meteor. However, calculation of fragmentation strength is model dependent, and fragmentation is a multistep process. Svetsov et al. [8] examined four well-documented falls that exhibited multiple fragmentation events: the Innisfree L5 OC, the Pribram H5 OC, the Lost City H5 OC, and the Sikhote-Alin IIAB iron. The first fragmentation occurred at very low dynamic pressure, but the major fragmentation occurred at much higher strength. The long space exposure ages of most stone meteorites suggests that they likely suffered multiple impacts which can produce cracks in the surface layer. Thus the earliest meteor fragmentation may simply correspond to shedding of weakly bound surface material. The Chelyabinsk meteor, for example, was modeled with fragmentation starting at 0.2 MPa

[9]. But Popova et al. [9] showed the major mass loss occurred in a single event at ~27 km (~18 MPa [10]), likely reflecting the bulk strength of the body.

Popova et al. [11] tabulated fragmentation strengths for meteors from the European Fireball Network, the Prairie Network, and the Satellite Network, covering an initial masses from ~20 g to >3x10^5 kg. They found considerable variation in strength at any given mass, but no clear variation of strength with mass.

Fragmentation strengths have been published for seventeen well-tracked meteors from which meteorites have been recovered (reviewed by Flynn et al. [5]). They ranged over more than four orders-of-magnitude in preatmospheric mass, from 1.5x10^3 g to 7.0x10^7 g. Of these, only one, the carbonaceous chondrite Maribo (T_J = 2.91), had a T_J value suggesting a possible cometary origin, but this is close enough to T_J = 3 that an asteroidal origin is also possible. These 17 events produced meteorites ranging from relatively weak carbonaceous chondrites to much stronger, thermally metamorphosed ordinary chondrites. Figure 2 shows their fragmentation strengths versus masses. The data scatter widely, likely reflecting the different types of meteorites included in the sample, but show no clear correlation of strength with mass. The best fit line to log σ vs log m gives a negative α value of -0.154, with r = 0.446, again showing that a large majority of the variation is scatter, likely from mixing different meteor compositions in a single data set, with less than 20% of the trend being explained by the correlation line. However, this data may be biased by the requirement that the meteor produce a recovered meteorite.

Brown et al. [10] found no trend of strength with size for >50 fireball events produced by meteors larger than 1 meter in size detected US Government Sensors (satellites). Only four of these events produced identified meteorites. Two of these fireballs reached the ground without fragmentation, indicating that a fraction of the incident population was even stronger than those for which fragmentation strengths were determined. Fragmentation strengths for the others were determined taking the altitude at the peak of luminosity of the trail as the indicator of major fragmentation event. These fireballs ranged over almost four orders-of-magnitude in mass, from 1.7x10^6 g to 1.2x10^{10} g, providing the opportunity to extend the meteor data to larger masses (Figure 2). Only a few these fireball meteors had Tj values less than 3, suggestive of cometary origin, so Brown et al. [10] suggested <15% of the objects from meters to hundreds of meters in size are cometary, with the remainder being asteroidal. The best fit gives α = -0.117, with r = 0.17. Again, less than 20% of the variation is explained by the correlation line, and the line shows a weak trend of increasing strength with mass.

Ideally, meteor data should be separated by type, but the number of events for which both spectroscopy and fragmentation strength are available is very small.

Comparison of Meteorite and Meteor Strength: Comparison of fragmentation strengths of meteors to compressive strength of meteorites of the same type has been taken to indicate that meteor strength decreases with increasing size [6]. However, this comparison presumes meteorite compressive strength and meteor fragmentation strength measure the same property. Slyuta [12] suggests tensile strength, which is much lower than compressive strength, is the correct analog to fragmentation strength, and that the range of tensile strengths of OC meteorites, 18 to 31 MPa, is comparable to fragmentation strengths of OC producing meteors like Chelyabinsk (~18 MPa [10]), Sayhal Uhaymir 001 (~16 MPa [4]) and Ghubara (~24 MPa [4]).

The currently available data on asteroid fragments provides no clear, compelling evidence for significant variation of strength with mass over the size range of meteorites and fragmenting meteors.

References: [1] Weibull, W. (1951) *J. App. Mech.,* 10, 140-147. [2] Hartmann, W. (1969) *Icarus*, 10, 201-213. [3] Yoshinaka, R. et al. (2008) *Eng. Geol.*, 96, 173-186. [4] Slyuta, E. (2008) *LPSC XX XIX*, #1056. [5] Flynn, G. et al., (2018) *Chem. der Erde*, 78, 269-298. [6] Cotto-Figueroa, D. et al. (2016) *Icarus*, 277, 73-77. [7] Zotkin, I. et al. (1987) *Meteorika*, 46, 86-93. [8] Svetsov, V. (1995) *Icarus*, 116, 131-153. [9] Popova, O. et al., (2013) *Sci. Exp.,* science.1242642 [10] Brown, P. et al. (2016) *Icarus*, 266, 96–111. [11] Popova, O. et al. (2011) *MAPS,* 46, 1525-1550. [12] Slyuta, E. (2017) *Solar Sys. Res.*, 51, 64-85.

Fig. 1: Mass vs compressive strength for meteorites.

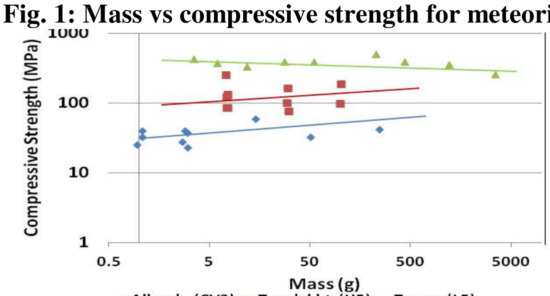

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Fig. 2: Mass vs fragmentation strength for meteors.