THE IMPACT RATE OF SMALL ASTEROIDS AT THE EARTH'S SURFACE. P. A. Bland[1] and N. A. Artemieva[2], [1]Department of Earth Science and Engineering, Exhibition Road, Imperial College London, South Kensington Campus, London SW7 2AZ, UK, p.a.bland@imperial.ac.uk; [2]Institute for Dynamics of Geospheres, Russian Acad. Sci., Leninsky Prospect 38/6, Moscow, Russia 117939, nata_art@mtu-net.ru.

Introduction: The craters preserved on the lunar mare provide a record of the rate of impacts and the impactor size distribution, over a mass range of ~10-10^{16}kg, for the 3.2-3.5Ga since the mare basalts were emplaced [1]. Constructing a similar curve for number of impacts over a given mass at the Earth's surface is complicated: the atmosphere disrupts meteoroids [2], and craters are removed by erosion and tectonism, infilled, or simply go unrecognised. A combination of these factors has given rise to the long-recognised departure from a simple power-law size distribution for terrestrial craters <20km in diameter [3]. Since the terrestrial small crater record is incomplete, and inadequate for constraining the flux at the surface, we have chosen to scale the known impact rate at the upper atmosphere to a flux at the surface by modelling how a given bolide behaves in the atmosphere.

Understanding the atmosphere-bolide interaction is crucial to determining a flux at the surface, but accurately modelling the fragmentation and ablation behaviour of bodies with different strength, composition, and mass, is a non-trivial task. Although there were early attempts to model separated impactor fragments [4,5], most subsequent semianalytical approaches have simplified the problem by considering the impactor as a strengthless liquid-like object: so-called 'pancake' models, in which clouds of fragments are modelled as a continuous, lower-density, deformed impactor [2,6-8]. Unfortunately, although 'pancake' models are of value in delineating, for example, the height at which bolides disrupt (e.g. [6]), they are not capable of reproducing the cratering behaviour of fragmented asteroids at the Earth's surface. In contrast, Artemieva and co-workers [9-11] have developed a model that calculates motion, aerodynamic loading, and ablation, for each individual particle or fragment. We have used the separated fragments (SF) model to understand fragmentation and ablation in the Earth's atmosphere for a range of impactor types and masses, in addition to a 'pancake' model [6], and a simple ablation model. The benefit of the SF approximation is that it allows us to define a mass-velocity distribution at the surface for solid fragments which either create craters (in the case of high final velocity) or which may be found as meteorites (fragments with low final velocity) ie. for a given impactor at the top of the atmosphere, it allows us to predict the mass- velocity-distribution for that impactor at the Earth's surface. The flux at the upper atmosphere has recently been well constrained over a large portion of the mass range [12-19]. In addition, asteroid spectroscopy [20-23] and impactor composition in large terrestrial craters [24] place constraints on the composition of the flux at the top of the atmosphere. A knowledge of the fragmentation and ablation behaviour for a given initial mass and impactor type allows us to estimate the energy and mass delivered to the surface, so that the flux curve for the upper atmosphere can be scaled to an impact rate at the Earth's surface.

Methodology: The SF model used here has been developed over several years, and is based on 3D hydrocode modelling [9,10]. It is described in detail elsewhere [10,11]. The model takes into account successive fragmentation and ablation of individual fragments. The meteoroid is subjected to disruption if dynamic loading exceeds tensile strength, which depends on the projectile type and size. The model simulates the evolution of a meteoroid consisting of a variable number of solid fragments. The number of fragments changes in the process of the calculation from 1 to an arbitrary value, depending on the properties of individual fragments. Fragments have higher strength than the initial body, but may be disrupted again later into a new pair, etc. The equation of motion [4] is solved for each individual fragment, with an additional equation describing repulsion. The cross-range spread is produced by the interaction of bow shocks after breakup, spreading velocity U (two identical fragments with density ρ_b, trajectory velocity V disrupted at the altitude with atmospheric density ρ_a) is defined as $U=CV(\rho_a/\rho_b)^{0.5}$ with C=0.01-1 from the analysis of the Earth's strewn fields. The idea is confirmed in 3D modelling of disrupted meteoroid motion [9,10]. The coefficient of repulsion C is defined as 0.45.

Two types of projectile are principally considered: irons with density of 7800kg/m^3, ablation coefficient of 0.07 s^2/km^2 and strength of 4.4x10^8 dyn/cm^2 (for 1kg sample) [10], and stones with density of 3400kg/m^3, ablation coefficient of 0.014 s^2/km^2 and 10x lower strength. The parameters for stones were chosen to define approximate upper limits on strength and density: larger stony bodies in the atmosphere, and carbonaceous bolides, may well have significantly lower strength and density. We performed 16 simulations for stony impactors using the SF model, and 16 for irons, for bodies from 1 to 10^8kg, repeating each simulation for a given mass >20 times to derive average impact conditions (in total >1000 SF model simulations were performed). 'Pancake' model simulations were performed over the range 1-10^{12}kg. All simulations were at average asteroidal impact velocities and entry angles: 18 km/s and 45º respectively.

Results and discussion: When the model outputs are compared we find that 'pancake' and SF model estimates of total surviving material at the surface coincide tolerably well for irons, but the same is not true for stones. A 'pancake' model with spreading to x2 initial radius is typically chosen, which significantly overestimates impactor survivability for stones over the whole mass range. SF and 'pancake' results only converge when we consider spreading to x4 initial radius (much larger than typically used) and only for initial masses >10^7kg (possibly as larger stones behave as a liquid-like 'swarm' of fragments).

SF modelling also quantifies the dramatically different survivability of iron and stony impactors. Over the mass range 10^3-10^7kg iron impactors transfer to the surface ~3 orders-of-magnitude more energy/unit area than stones: a fragmented iron impactor of 10^5kg produces a similar crater-field to a fragmented 10^8kg stone (Figure 1). Even larger stony bodies of ~10^8-10^{10}kg are much less efficient at transferring energy to the surface

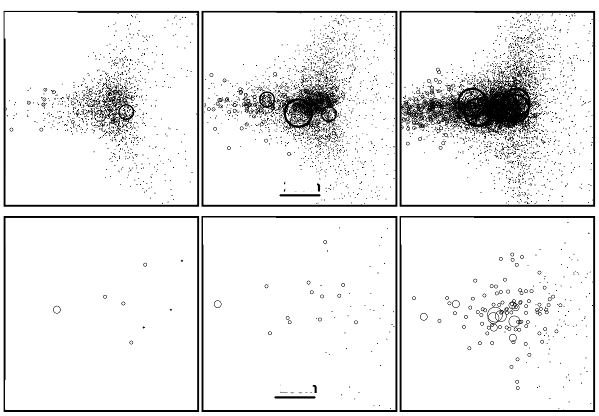

Figure 1. Crater fields for iron (top row) and stony (bottom row) bodies for a range of pre-entry masses. Sizes of circles approximately equal the size of impact craters - dots are for <10m pits. For stones, although a small percentage of the impactor reaches the surface, even a 10^8kg mass does not lead to impact crater formation.

than the equivalent iron impactor. SF model simulations constrain the mass- velocity-distribution of these fragments, allowing us to derive morphologies of simulated crater fields. The SF results are in good agreement with terrestrial crater records, and also with available meteorite data.

A compilation of flux data for the top of the Earth's atmosphere [12-19] is found to match the size-frequency distribution of impactors derived from the lunar mare crater record [25,26] (after crater data is scaled to projectile diameter [27,28]) to within a factor of 3 over 16 orders of magnitude. We therefore take this curve for our flux at the upper atmosphere, and scale it to a flux at the surface based on our database of impact simulations and an estimate of impactor composition at the upper atmosphere [20-24].

Conclusion: This analysis constrains the impactor flux at the Earth's surface over the mass range 10^2-10^{12}kg. Our data indicate a significantly lower surface flux than some previous studies have suggested [29].

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