A NEW APPROACH TO ESTIMATE METEOROID IMPACT HAZARD BASED ON ATMOSPHERIC TRAJECTORY ANALYSIS. M. Gritsevich[1,2,3], E. A. Silber[4], E. Lyytinen[3], M. Moreno-Ibáñez[5,6], J. M. Trigo-Rodríguez[5], K. Muinonen[1,6], A. Penttilä[1], R. E. Silber[7], [1]Department of Physics, University of Helsinki, PO Box 14, FI-00014, Finland, maria.gritsevich@helsinki.fi, [2]Institute of Physics and Technology, Ural Federal University, Mira street 19, 620002 Ekaterinburg, Russia; [3]Finnish Fireball Network, esko.lyytinen@jippii.fi; [4]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, 02912, USA, elizabeth_silber@brown.edu; [5] Institute of Space Sciences (IEEC-CSIC), Meteorites, Minor Bodies and Planetary Science Group, Campus UAB, Carrer de Can Magrans, s/n E-08193 Cerdanyola del Vallés, Barcelona, Spain, mmoreno@ice.csic.es, trigo@ice.csic.es; [6]Finnish Geospatial Research Institute (FGI), National Land Survey of Finland, Geodeetinrinne 2, FI-02430 Masala, karri.muinonen@helsinki.fi, antti.i.penttila@helsinki.fi, [7]Department of Earth Sciences, University of Western Ontario, London, Ontario, Canada, N6A 5B7

Introduction: One of the important steps in the prediction of an impact threat to Earth raised by potentially hazardous asteroids is the understanding and modeling of the processes accompanying the object's entry into the terrestrial atmosphere. Such knowledge enables characterization, simulation and classification of possible impact hazards. The spectacular Chelyabinsk bolide [1] is a testament to the need to improve and further develop methodologies that would help in estimating impact threat. The reconstructed atmospheric trajectory is the key to deriving the pre-impact meteoroid's orbit in the Solar System and it is also a prerequisite for dark flight simulations that enable us to follow surviving meteorite fragments all the way to the ground. We have developed the parametrization model to describe the changes in mass, height, velocity and luminosity of the object along its atmospheric path. The model takes into account real atmospheric conditions and can be used to estimate, among other parameters, ablation rate, and survived meteorite mass. We demonstrate its application using the wide range of observational data from meteors to larger scale impacts. In particular, this approach enabled us to recently recover the Annama meteorite which was observed by the Finnish Fireball Network on 19 April 2014 [2].

Theory: We gather the unknown values in meteor physics equations into two dimensionless variables: α - ballistic coefficient, β - mass loss parameter [3] The analytical solution of these equations, with the initial conditions $y = \infty$, $v = 1$ and $m = 1$, leads to:

$$m = exp[-(1-v^2)\beta/(1-\mu)]$$

$$y = ln2\alpha + \beta - ln\Delta, \quad \Delta = \bar{E}i(\beta) - \bar{E}i(\beta v^2),$$

$$\bar{E}i(x) = \int_{-\infty}^{x} \frac{e^t dt}{t}$$

where

$$\alpha = \frac{1}{2} c_d \frac{\rho_0 h_0 S_e}{M_e sin\gamma}\ ;\ \beta = (1-\mu)\frac{c_h V_e^2}{2 c_d H^*}$$

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Adjusting the (v, y) values to the trajectory observed (v_i, y_i) values by means of a weighted least-squares method, one can derive the corresponding parameters (α, β) for each meteoroid. Atmospheric conditions are taken into account as described by [4]. Using this approach, one can estimate e.g. the observed fireball terminal heights by applying the formula [3]:

$$h_{III} = h_0 \cdot y_t = h_0 \cdot ln\left(\frac{2\alpha(\beta-1.1)}{\left(1-e^{(\beta-1.1)(v_t^2-1)}\right)}\right)$$

Results: The results for the fireball cases obtained by the Meteorite Observation and Recovery Project (MORP, operated in Canada in 1970-1985) are shown in Figure 1 [5]. The upper curve separates the 'meteorite production' region, and the lower curve denotes the region of crater formation. Our results suggest that there are specific cutoffs which could predict whether the given event would produce meteorites, and possibly even craters. The results for Košice, a representative meteorite producing fireball, are shown in Figures 2 and 3 [6]. The observed versus calculated terminal heights [3] for the MORP fireballs across all events are shown in Figure 4. As shown in Figure 4, the calculated heights are in excellent agreement with the observations. Both figures demonstrate that the new parametrization methodology can reliably produce results consistent with the observed values.

Summary: We present a new approach, developed by [4], to estimate the terminal height of impacting bolides, which is an essential step in evaluating the impact hazard. Subsequent testing of this new methodology has shown that the results are consistent with observations.

References: [1] Brown P. et al. (2013) *Nature*, 503, 238-241. [2] Trigo-Rodríguez J.M, et al. (2015), *MNRAS 449 (2), 2119-2127*. [3] Moreno-Ibáñez M. et al. (2015), *Icarus*, 250, 544-552. [4] Lyytinen E. and Gritsevich M. (2016), *Planet. Space Sci.*,120, 35 -42. [5] Gritsevich M. et al, (2012) *Cosmic Research, 50*

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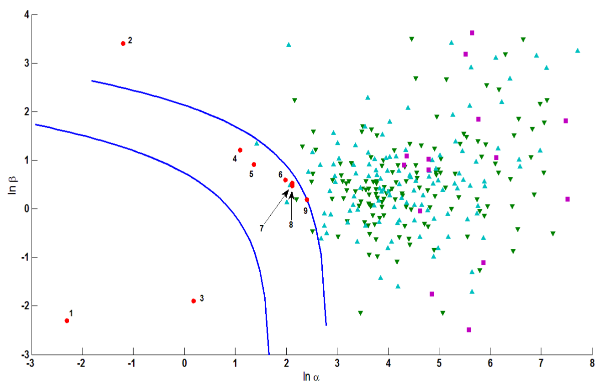

Figure 1: Results obtained by means of the described model based on observations. Fireballs detected by: ▼ - the Meteorite Observation and Recovery Project in Canada; ▲ - the US Prairie Network; ■ - the European Fireball Network. Highlighted events are denoted with ●, (1) – Crater Barringer; (2) – Tunguska; (3) – Sikhote-Alin; (4) – Košice; (5) – Neuschwanstein; (6) – Benešov; (7) – Innisfree; (8) – Annama; (9) – Lost City. Upper curve separates 'meteorite production' region, lower curve stands for crater formation.

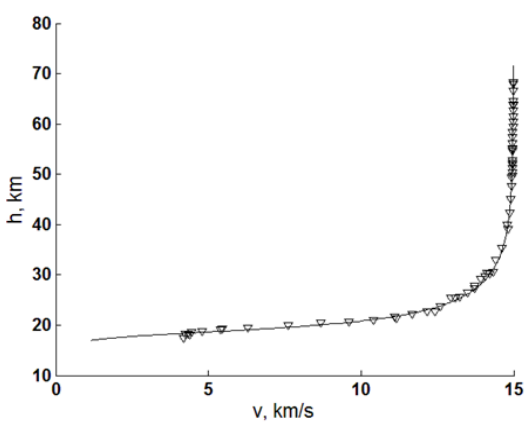

Figure 2: Results of calculations for the Košice meteoroid: Height vs velocity (main fragment).

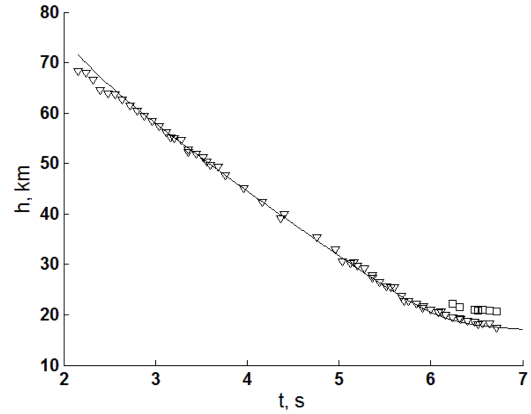

Figure 3: Results of calculations for the Košice meteoroid: height vs time (main fragment).

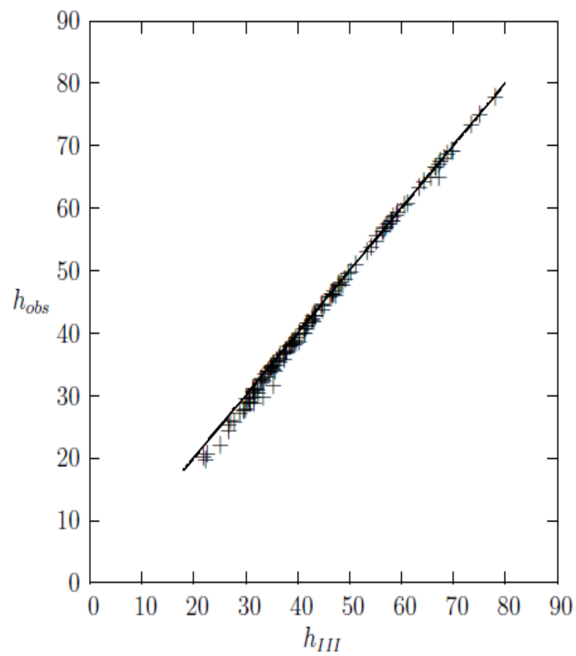

Figure 4: Observed terminal heights vs. calculated terminal heights for the MORP fireballs.