Goldilocks and the Three Catastrophic Fragmentation Airburst Models

S. McMullan and G. S. Collins

Impact and Astromaterials Research Centre, Dept. Earth Science and Eng. Imperial College London, SW7 2BP, UK (s.mcmullan16@imperial.ac.uk)

1. Introduction

- NEO's 1-100 m radius are abundant, difficult to observe and may strike Earth with little to no warning[1,2].

Fig. 1: Photo of the Chelyabinsk Fireball (Chelyabinsk.ru).

- Fast models of airbursts are imperative for probabilistic hazard assessment.
- Here we compare three existing catastrophic fragmentation models to see which is most appropriate for probabilistic hazard assessment.

2. Model Comparisons

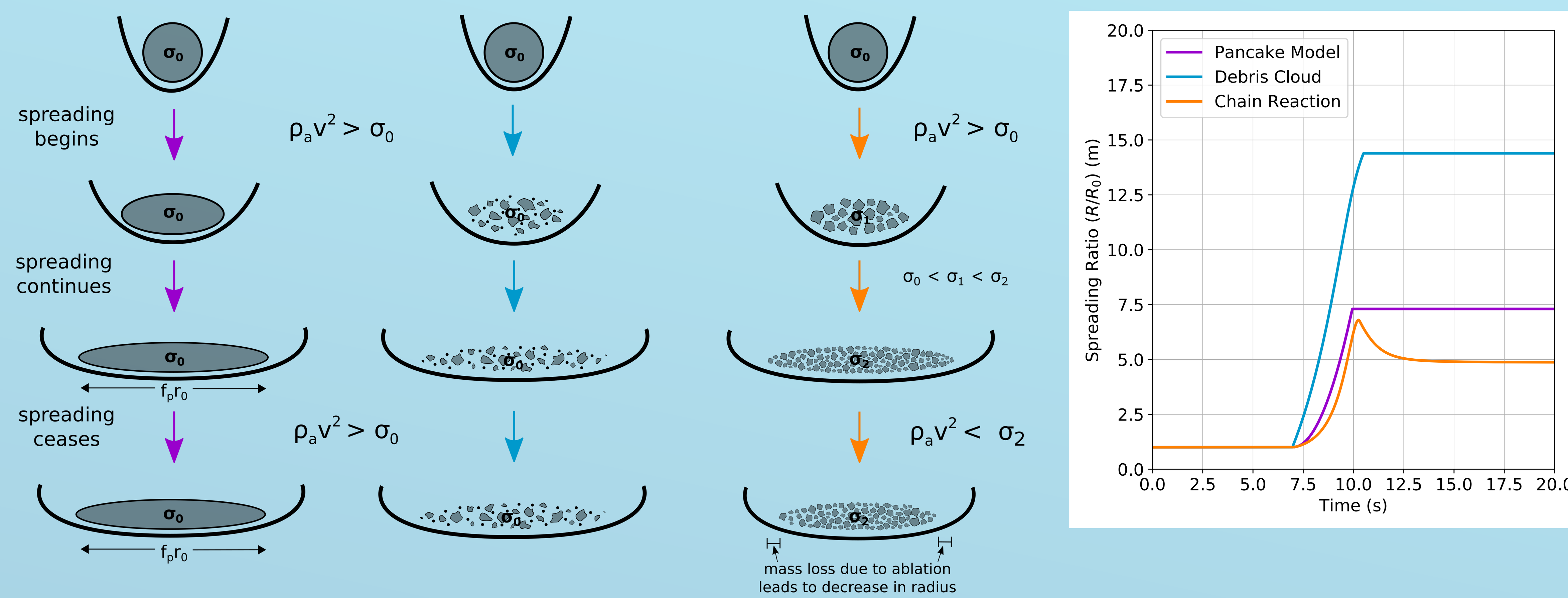

Fig. 2: Schematic diagram of each of the three models; **a)** the pancake model, as described by Chyba et. al, 1993[3], **b)** the debris cloud model, as described by Hills and Goda, 1993[4], and **c)** the chain reaction model, as described by Avramenko et. al, 2014[5], and **d)** their effect on the meteoroid's radius with time. Radius comparison (d) modelled with Chelyabinsk initial conditions (Table 1b) but all initial strengths are 0.5 MPa, α = 1 and β = 0.18, which are the values stated in the original papers[4,5]. Equations available on request.

3. Model Setup

a)	Pancake	Debris Cloud	Chain Reaction
σ_0 (MPa)	0.75	0.9	0.45
f_p / α / β	7.3	0.3	0.172

All models: C_D = 1.5, C_H = 0.12, and Q = 1 x 10^7 J/kg.

b)	Chelyabinsk	Tunguska (Nominal)	Tunguska (Best Fit)
v_0 (km/s)	19.04	20	15
r_0 (m)	9.95	28	36
θ_0 (°)	17	45	45
ρ_0 (g/cm³)	3.3	3.3	2.8
E_{tot}	0.5	15	15

Table 1: Model setup conditions for both Chelyabinsk[5] and Tunguska with a) showing the variation in unconstrained parameters when calibrated to Chelyabinsk and b) showing the initial conditions of both Chelyabinsk, Tunguska nominal values and the best fit for Tunguska.

4. Results

- All models can be calibrated to fit Chelyabinsk data, but require different initial strengths.
- When up-scaled to a Tunguska size impact the height of peak energy depositions differ between models.

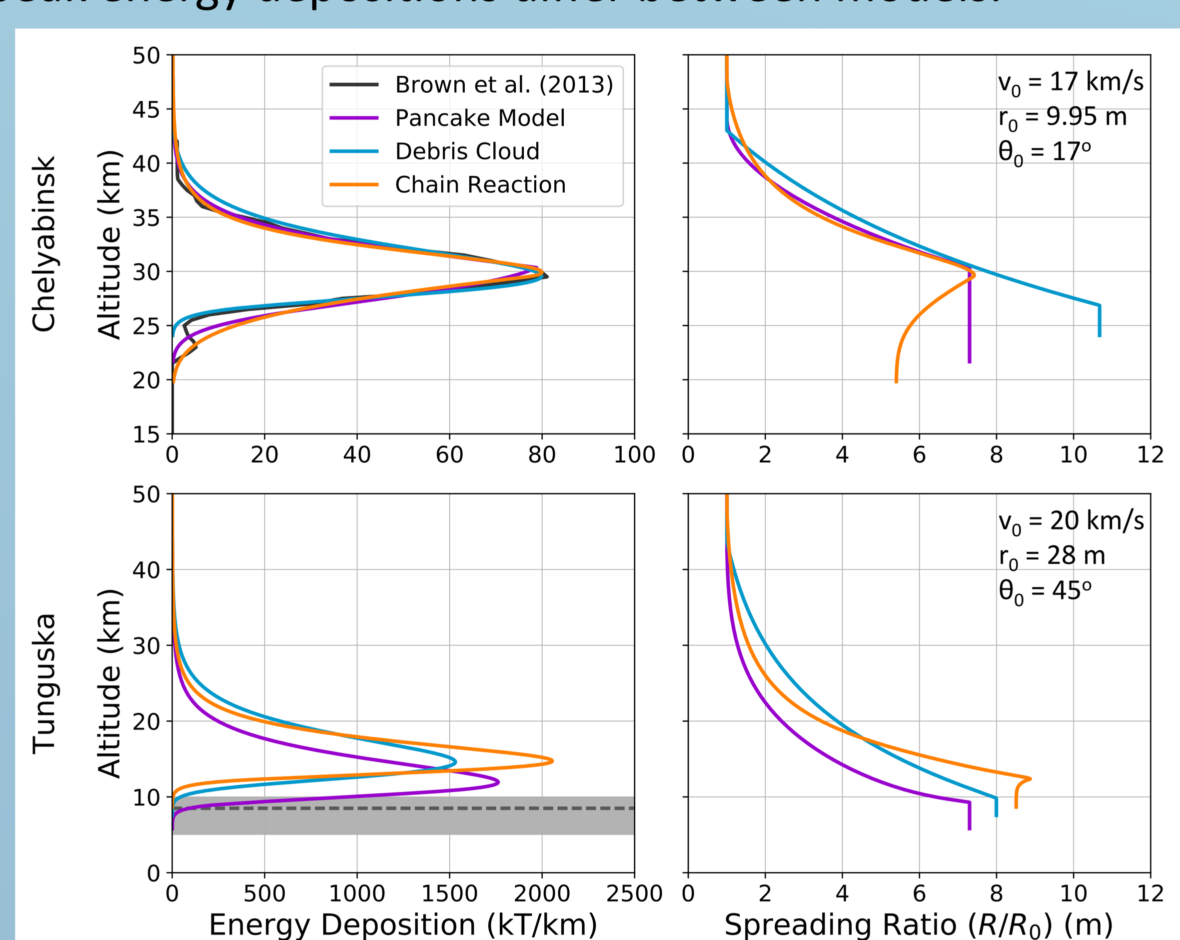

Fig. 3: Comparison of the three models when they are calibrated to Chelyabinsk (top) and then up-scaled to a Tunguska scale impactor (bottom). The figures on the right show the differences in meteoroid radius with altitude for each model and both impactors. The grey area on the Tunguska energy plot shows the estimate burst altitudes, with the dashed line at 8.5 km[3,6,7,8].

5. Increasing Strength as a Pancake Factor

- Adding increasing strength[9] with decreasing fragment size to the pancake model provides physical rationale for the spreading limit.
- Pancake model now agrees with the chain reaction model's initial strength however a slightly smaller β of 0.157 (rate of spreading) is required.

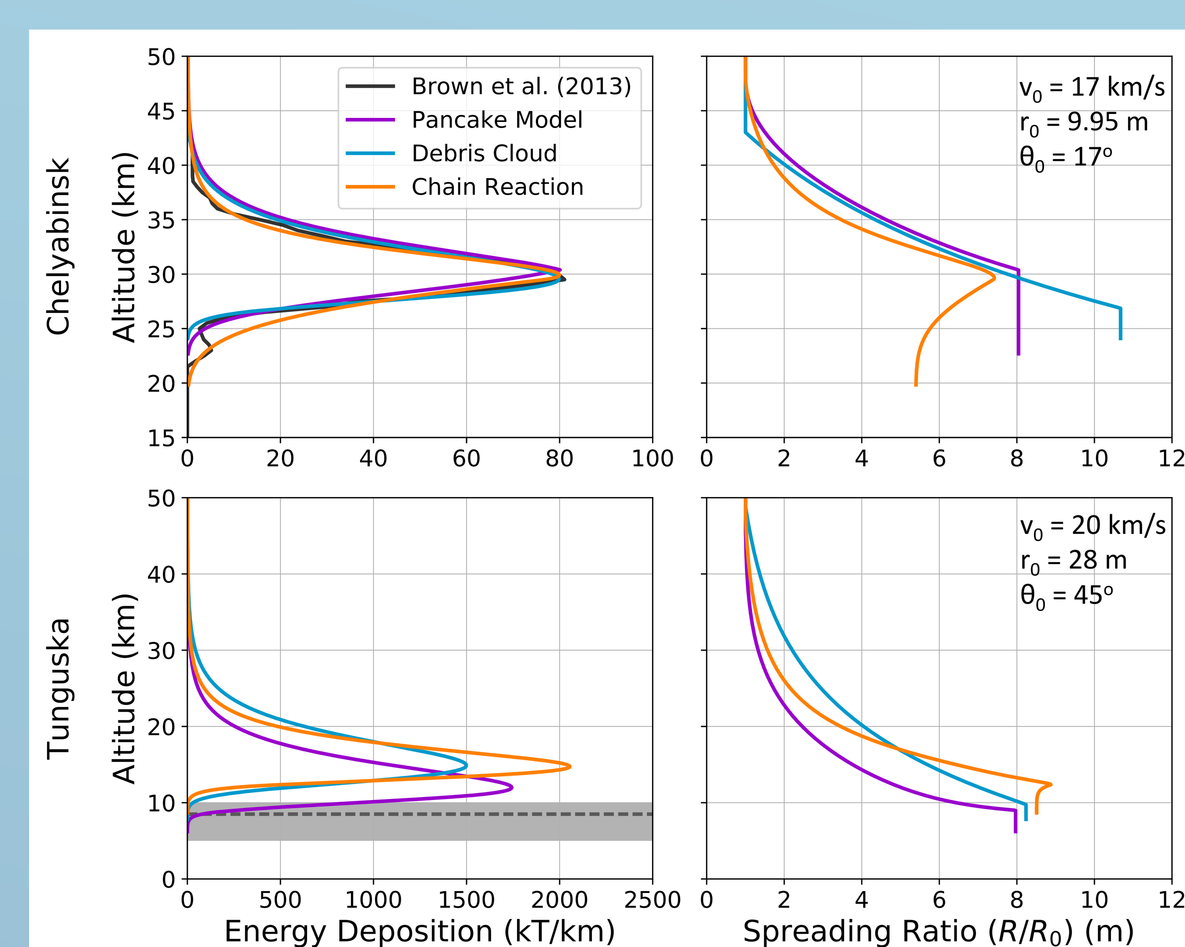

Fig. 4: Same as Fig. 3 with the introduction of increasing strength to the pancake model. The pancake model no longer requires a pancake factor and σ_0 = 0.45 and β = 0.157.

6. Tunguska Best Fit

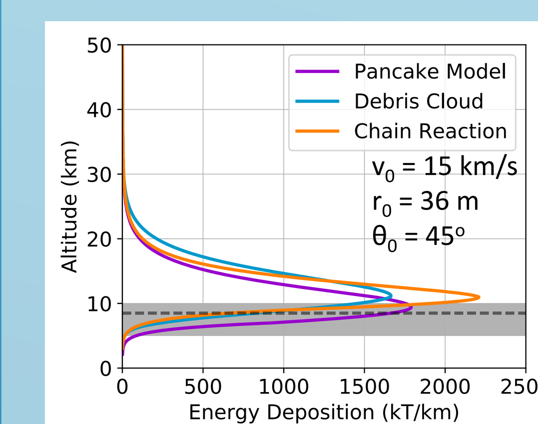

Fig 5: (left) Best fit of the models to the inferred burst altitude of Tunguska. Table 1b contains initial condition required with 5xσ_0 in Fig. 4. (right) Photo by Kulik of the treefall damage at Tunguska.

7. Conclusions

- *All models can be tuned to fit data, but extrapolate differently.*
- *Probabilistic hazard assessment should include inter-model uncertainty.*
- *A more realistic treatment of fragment strength provides a physical rationale for spreading limits.*
- *Extrapolation is difficult with only one calibration point. Another well documented large fireball would help constrain parameters.*
- *Models make very different assumptions on spreading rate; an independent study of spreading rate could help constrain parameters and reduce error in predicted potential damage area.*

References: [1] Brown P. G. et al. (2013) *Nature, 503,* 238-241. [2] Popova O. P. et al. (2013) *Science, 342,* 1069-1073. [3] Chyba C. F. et al. (1993) *Nature, 361,* 40-44. [4] Hills J. G. and Goda M. P. (1993) *Astron. J., 105, 3,* 1114-1144. [5] Avramenko M. I. et al. (2014) *JGR, 119,* 7035-7050. [6] Artemieva N. A. And Shuvalov V. V. (2016) *Annu. Rev. Earth Planet. Sci., 44,* 37-56. [7] Ben-Menahem A. (1975) *Phys. Earth Planet. Inter., 11,* 1-35. [8] Boslough M. B. E. and Crawford D. A. (1997) *Ann. N.Y. Acad. Sci., 822,* 236-282. [9] Weibull W. (1951) *J. Appl. Mech. Trans., ASME 18,* 293-297. **Acknowledgment:** This work was funded by STFC grant ST/N000803/1.

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