Comparison of Thermal Radiation Damage Models and Parameters for Impact Risk Assessment

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Introduction

- Thermal radiation can produce substantial damage in some cases
- Asteroid risk assessments have typically estimated thermal radiation using nuclear-based engineering-level models
- Large uncertainties remain in luminous efficiency parameter used to represent how much energy contributes to thermal damage
- Compare damage area predictions for two models – Collins et al. (2005) adjusted for airbursts as used in NASA's PAIR model (Mathias et al. 2017), and Johnston and Stern (2019)

Collins Model

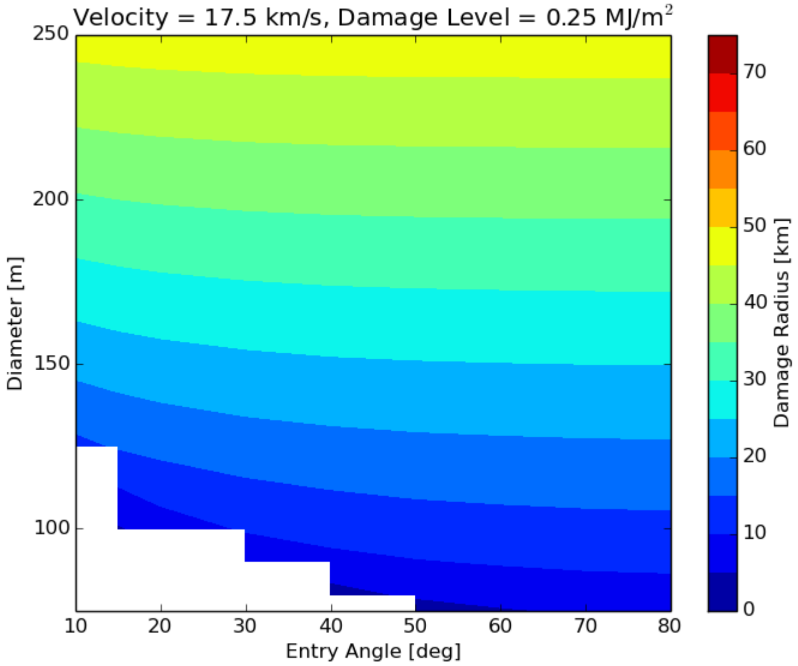
- Empirical model that predicts thermal radiation damage caused by spherically expanding fireball generated from impact
- Based on energy-scaled nuclear data (Glasstone and Dolan 1977)
- Luminous efficiency is an uncertain parameter – nominal value 0.003, range of 1e-4 to 1e-2 (Ortiz et al. 2000)

Johnston-Stern Model

- Higher-fidelity asteroid entry radiation model
- Fully coupled reacting flow and line-by-line radiation simulations to determine radiation burn area from shock-layer and wake of asteroid entry/airburst
- No luminous efficiency value needed

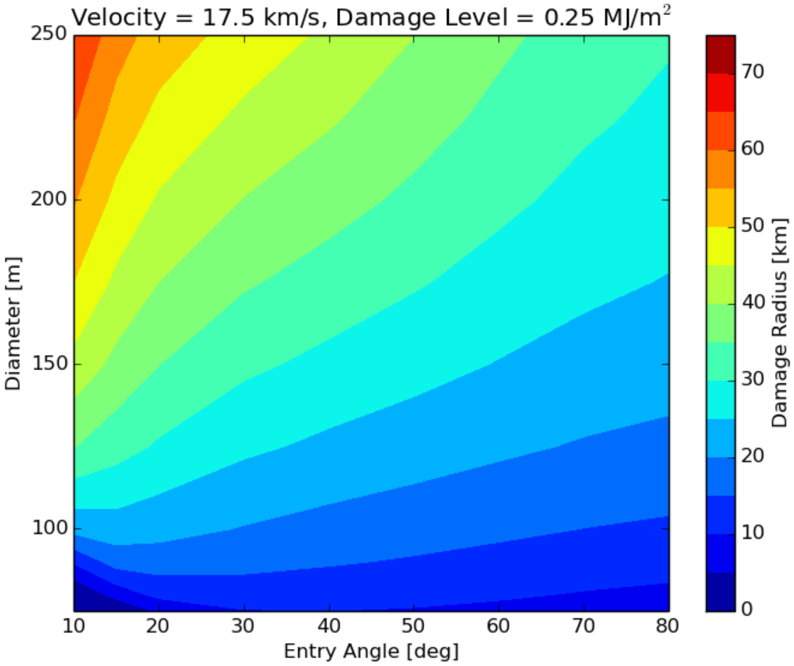
Damage Radius Comparisons

Collins Model



Damage radius determined by Collins Model for range of diameter and entry angle values for the 2nd degree burn damage level and assuming a nominal luminous efficiency value of 0.003

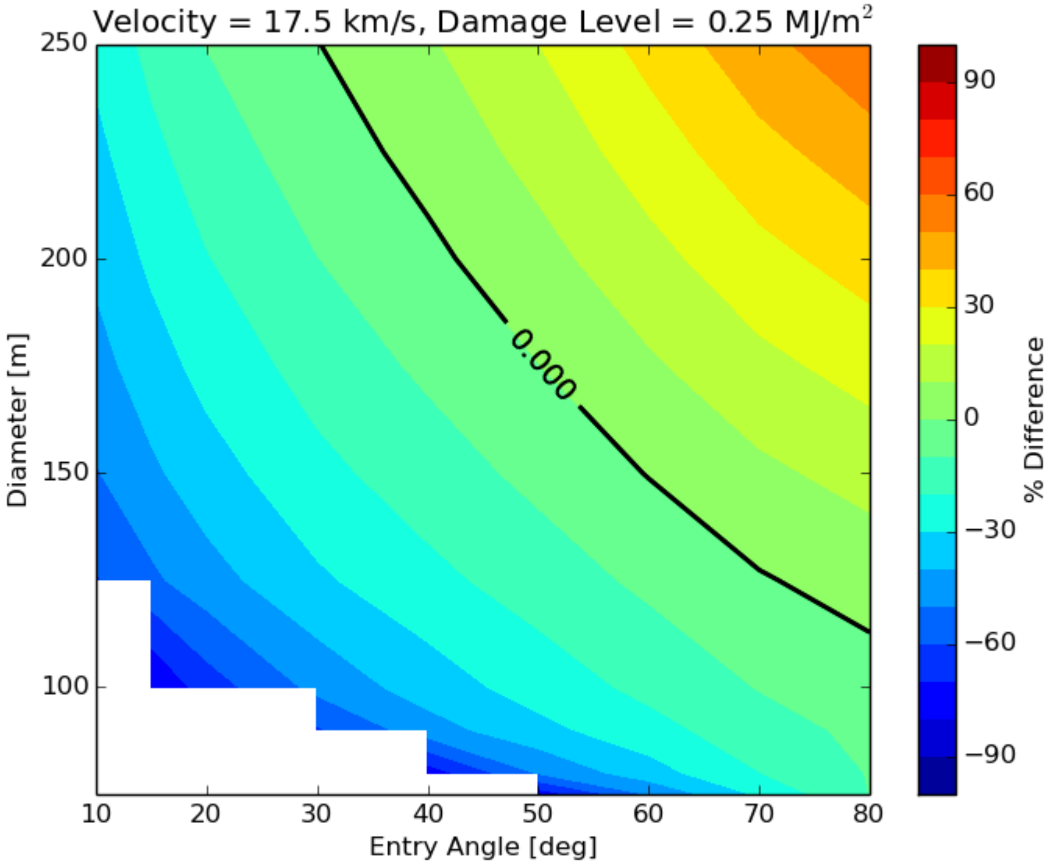
Johnston-Stern Model



Damage radius determined by Johnston-Stern Model for range of diameter and entry angle values for the 2nd degree burn damage level

Damage Radius Comparisons

$$\% \, Difference = \frac{Collins - Johnston\ Stern}{Johnston\ Stern} * 100$$



Percent difference between damage radius predictions for the two models assuming a nominal value of 0.003 for Collins

Damage Radius Comparisons

- Trends differ between results
  - Collins model does not directly account for entry angle and the only variation across entry angle for a given diameter in these plots is through the airburst height (maximum energy deposition height) in the modified model resulting in limited changes across entry angle
  - Johnston-Stern model takes entry angle into account more directly through the detailed simulations resulting in variations across diameter and entry angle
- All parameters used in the comparison – impact energy, airburst height (maximum energy deposition height), damage level/heat load – are the same between models for each case
- White area in the lower left corner of the Collins model prediction (shallow entry angles, smaller diameters) represents cases where the Collins model produced a non-physical damage area
  - Luminous efficiency of 0.003 was below the minimum allowable for those cases
- Results are presented for a velocity of 17.5 km/s and the 2nd degree burn damage level, study has been extended to additional velocities and damage levels with similar overall conclusions

Luminous Efficiency

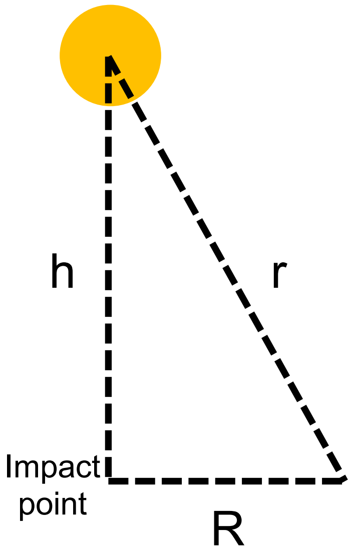
- A constant nominal luminous efficiency value of 0.003 appears insufficient
- Need to determine what luminous efficiency values are required in the Collins model to improve the comparison between the models
- Modify Collins model to account for airbursts as in NASA's PAIR thermal model

Solve for luminous efficiency (η) to match damage radius

$$\eta = \frac{2\pi r^2 \phi}{E}$$

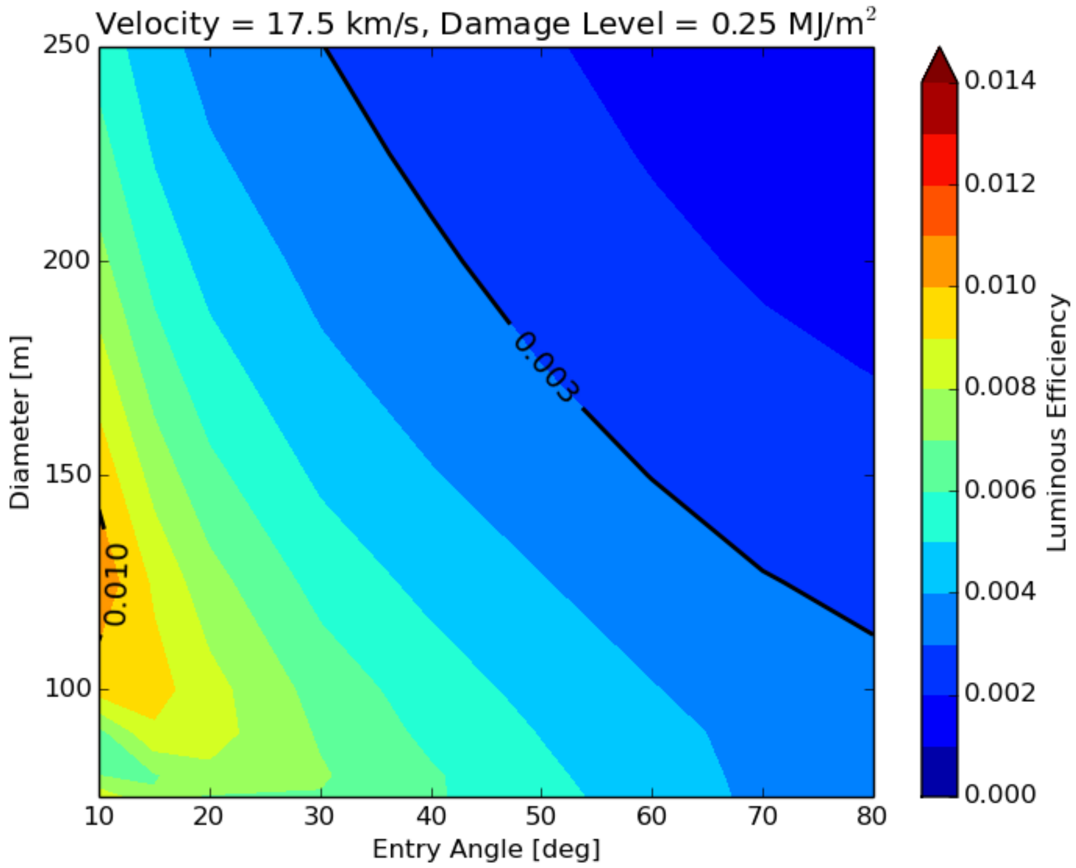
$$\phi = \phi_i(1\ Mt) E_{Mt}^{\frac{1}{6}}$$

$$r = \sqrt{R^2 + h^2}$$



h: Airburst height
R: Damage radius
E: Impact energy
ϕ: Heat load
$\phi_i(1\ Mt)$: Damage level

Luminous Efficiency

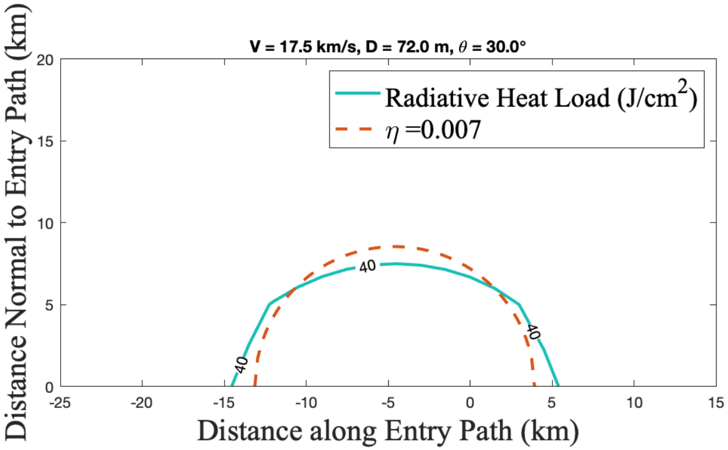


Luminous efficiency values needed in the Collins model to match the damage area determined by the Johnston-Stern model

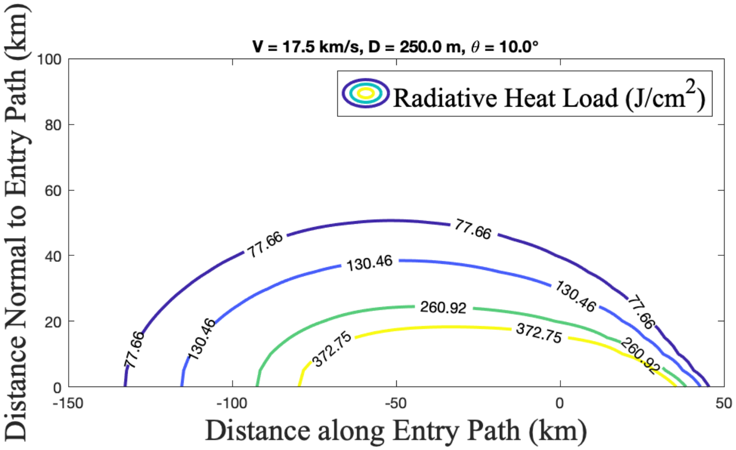
Largely within accepted uncertainty range of 1e-4 to 1e-2

Conclusions

- Can match damage area determined from the Johnston-Stern model with the adjusted Collins model using luminous efficiency values within the accepted uncertainty range (1e-4 to 1e-2) – positive result for ensemble risk calculations that sample within this uncertainty range
- Collins model only predicts circular damage areas while the Johnston-Stern model predicts non-circular damage areas – Johnston-Stern more desirable for specific cases where damage location is important



Tunguska case highlighting difference in shape between Johnston-Stern model (radiative heat load) and Collins model (η=0.007) for same damage area



Johnston-Stern model predictions for 4 damage levels at a shallow entry angle clearly showing non-circular damage areas. Non-circular areas are particularly apparent at shallow entry angles

Moving Forward

- Further analyze additional damage levels, 4 computed so far with the 2nd degree burn level presented here
- Extend the study to bigger diameter asteroids where thermal radiation damage would exceed blast damage, currently diameters go up to 250 m

- Work towards incorporating the Johnston-Stern thermal radiation damage model into NASA's Probabilistic Asteroid Impact Risk (PAIR) model (Mathias et al. 2017) to capture more specific cases
  - Consider how to parameterize the Johnston-Stern model to update the PAIR thermal model based directly on asteroid properties or entry energy deposition models – move away from adapting Collins model with varying luminous efficiencies
  - Determine how to bridge the gap between the assumptions and approach of the Johnston-Stern model, including use of the pancake model, with PAIR

References

Collins, G.S., Melosh, H.J, Marcus, R.A, 2005. Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth. Meteoritics & Planetary Science 40, 817-840.

Glasstone, S., and Dolan, P., 1977. The Effects of Nuclear Weapons. U.S. Government Printing Office, Washington D.C..

Johnston, C.O., Stern, E.C., 2019. A model for thermal radiation from the Tunguska airburst. Icarus, 327, 48–59. https://doi.org/10.1016/j.icarus.2019.01.028

Mathias, D.L., Wheeler, L.F., Dotson J.L., 2017. A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009

Ortiz J. L. et al., 2000. Optical detection of meteoroid impacts on the Moon. Nature 405:921–923.

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