Automated Fragmentation Modeling of Jupiter Impacts

Kathryn Davis [1] Ramanakumar Sankar [2] Csaba Palotai [1]

[1]Department of Aerospace, Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL, USA
[2]Center for Integrative Planetary Science University, University of California, Berkeley, Berkeley, CA USA

Abstract

Over the past 30 years, impact observations on Jupiter have provided unique opportunities to investigate the effects of mid- to large-sized collisions on atmospheres. Many of the observations made for these impacts are either earth-based or from a distance large enough that we cannot see certain aspects of the impact event. These include the entry angle, speed, and impactor type (icy, rocky, or metallic). In order to understand how the meteor interacts with not only Jupiter's atmosphere but atmospheres as a whole, it is important to constrain those properties associated with the event. We find probable combinations of these parameters by modeling the light curve produced by the impactor and comparing it with the observed data. In the past, it has been found that several different scenarios can produce satisfactory results. In this work, we implement the model fitting code, DNest4, into the preexisting fragmentation model [2] to automate the different combinations that can occur. The expanded model provides the initial parameters that best fit the observed data. We first test the models with the Jovian impact of August 7, 2019, and further use it to model the impact of November 23, 2023. We find that the latter is likely metallic in composition, and had an entry angle and speed of 24 degrees and 60 km/s, respectively. We acknowledge support for this project by NASA's Solar System Workings Program (Grant No. 80NSSC22K1376).

Overview and Motivation

- Constrain different physical and dynamical properties of Jovian impactors for future atmospheric simulations in order to understand the effects of mid-sized impactors on planetary atmospheres as a whole.
- **Why Jupiter:** On Earth, the number of 10-m sized impactors that occur is estimated to be $1\text{x}10^{-8}$ annually [3], while for Jupiter this estimate is between 4-25 annually [1].
- **Why mid-sized meteors:** Large (hundreds of meters to km in radius) sized meteors always reach the surface, while small pebble-sized meteors burn up harmlessly in the atmosphere. Mid-sized (few tens of meters in radii) can do either, or they can explode in the atmosphere triggering harmful shock waves (e.g. Chelyabinsk impactor).
- **Importance of automation:** The fragmentation model [2] was originally created to constrain those different properties by trial and error. Unfortunately, the process can be quite tedious as parameters are varied manually, significantly limiting both the number of parameters as well as the number of values tested within a given range. Automation increases both range and number of values while also reducing the workload on the researcher.

The Models

Fragmentation Model

- The fragmentation model simulates a light curve based on the given parameter space which we compare with the observed light curve to determine feasibility of different tested parameters.
- **Initial Parameters:** Total Energy, **Velocity (v)**, **Entry Angle (θ)**, **Bulk Density (ρ)**, **Material Strength (σ)**, **Ablation Coefficient (σ_{ab})**, Strength-Scaling Relation, and Dispersion Relation. Bold parameters are those that we vary.
- The model simulates the main body light curve from these given values, while discrete fragmentation events are manually added by the user, each defined with their own release properties.

DNest4

- DNest4 [4] uses Diffusive Nested Sampling to explore the given parameter space.
- The code computes the marginal likelihood (Z), which tells us the plausibility of the model.

$$Z = \int \mathcal{L}(\theta)\,\pi(\theta)\,d\theta \qquad (1)$$

- In its current state, the automation of the fragmentation model is limited to light curve simulations of the main body with no additional fragments. Fragmentation events are still added by the user with their individual properties.

Results

Code Validation: 7 August 2019 (AUG19)

Parameter	Input	Output
v [km/s]	60	65
θ [degrees]	65	76
ρ [kg/m^3]	500	4000
σ [kPa]	10	200
σ_{ab} [kg/J]	2x10^{-8}	3x10^{-9}

Table 1. Main body results from the automated model for the 7 August 2019 light curve. We utilize the results from Sankar et al. (2020) for their best-fit case as an initial guess for our model.

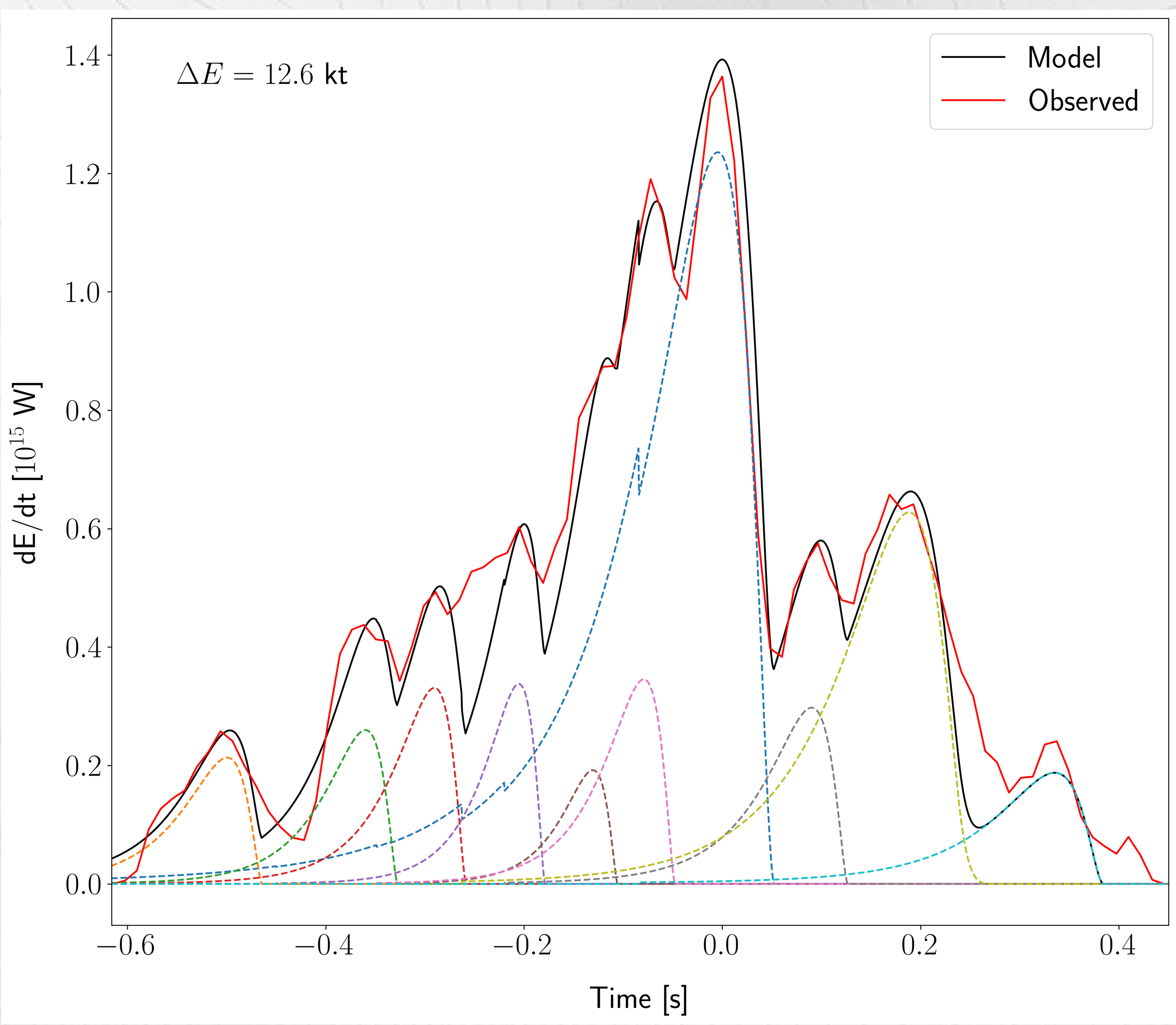

Figure 1. Match between the observed and modeled light curves for the 7 August 2019 impactor. The average residual between the two curves is shown in the top left. 12.6 kt TNT accounts for 11.2% of the total deposited energy. Colored curves represent the individual fragmentation events that contribute to the overall shape of the modeled light curve.

Results (continued)

15 November 2023 (NOV23)

Parameter	Input	Output
v [km/s]	65	60
θ [degrees]	20	24
ρ [kg/m^3]	800	4893
σ [kPa]	100	667
σ_{ab} [kg/J]	2x10^{-9}	1x10^{-9}

Table 2. Main body preliminary results from the automated model of the 15 November 2023 light curve.

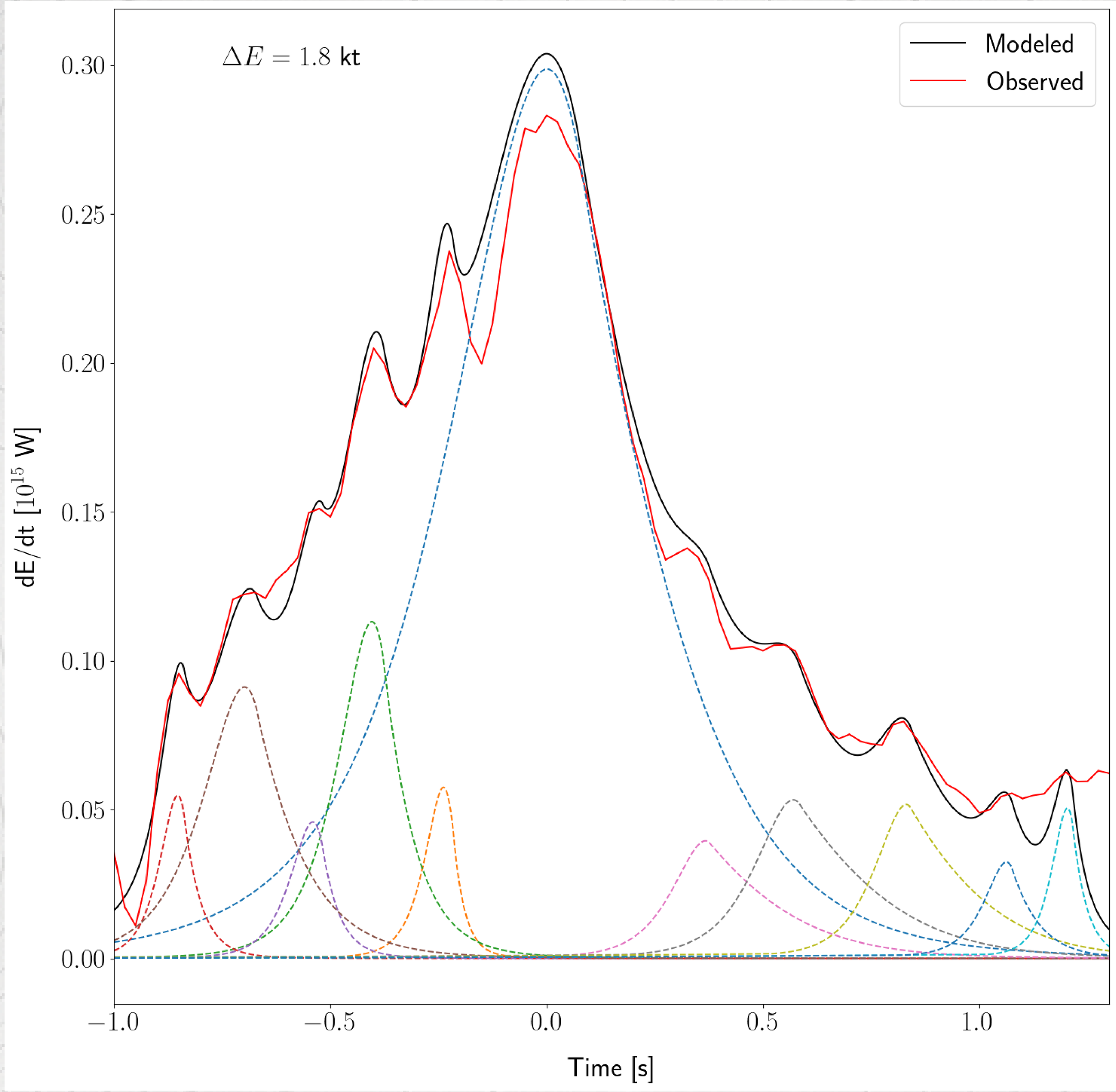

Figure 2. Match between the observed and modeled light curves for the 15 November 2023 impactor. The average residual between the two curves is shown in the top left. Results contributing to this modeled light curve are still preliminary. Colored curves represent the individual fragmentation events that contribute to the overall shape of the modeled light curve.

Conclusions

AUG19

- The simulated light curve fits with an 11.2% error, where previous fits for this impact have gone as low as 11.7% [2].
- The output parameters don't change significantly from the input with the exception of the density. The high density, low ablation coefficient and low bulk strength, indicate a stony meteor with a fractured surface.

NOV23

- Preliminary results show a good fit between the modeled and observed light curve with a 2.43% error.
- Similarly to our validation case, the density has the largest difference between input and output. High density, low ablation coefficient and low strength indicate a loosely packed metallic meteor.

Future Work

- Simulate the atmospheric response to the meteor using the ZEUS-MP 2 hydrodynamic model. An example of an expected output is shown in Fig. 3.

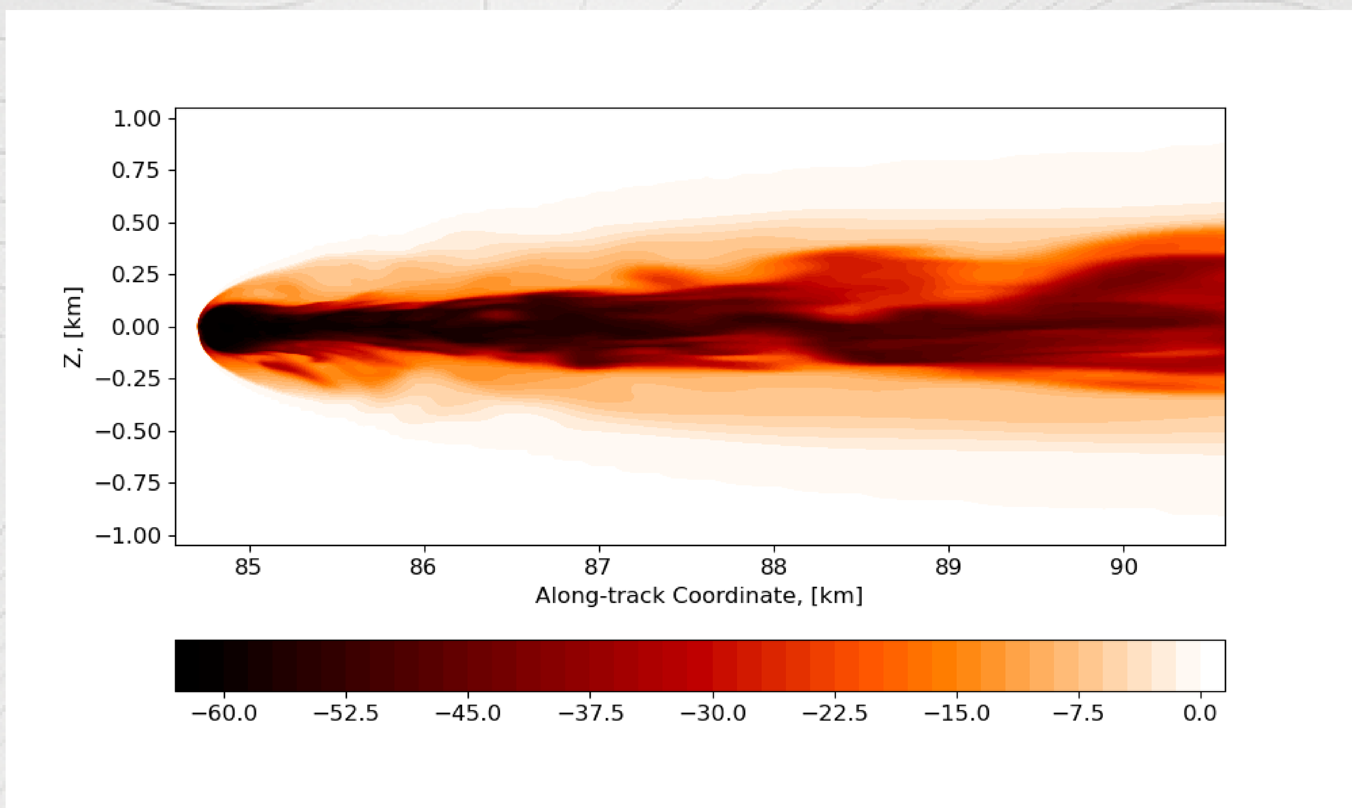

Figure 3. Along-track velocity for a 100-m simulated impactor using ZEUS-MP 2. Darker regions denote high velocity. Negative values are indicative of the direction of motion.

References

[1] Hueso et al. 2013 DOI:10.1051/0004-6361/201322216 [2] Sankar et al. 2020 DOI:10.1093/mnras/staa563 [3] Ivanov 2008 Catastrophic Events Caused by Cosmic Objects p.91-116 [4] Brewer et al. DOI:10.48550/arXiv.1606.03757

Florida Institute of Technology kdavis2017@my.fit.edu