How the breakup of triaxial asteroids generates debris reservoirs for white dwarf pollution

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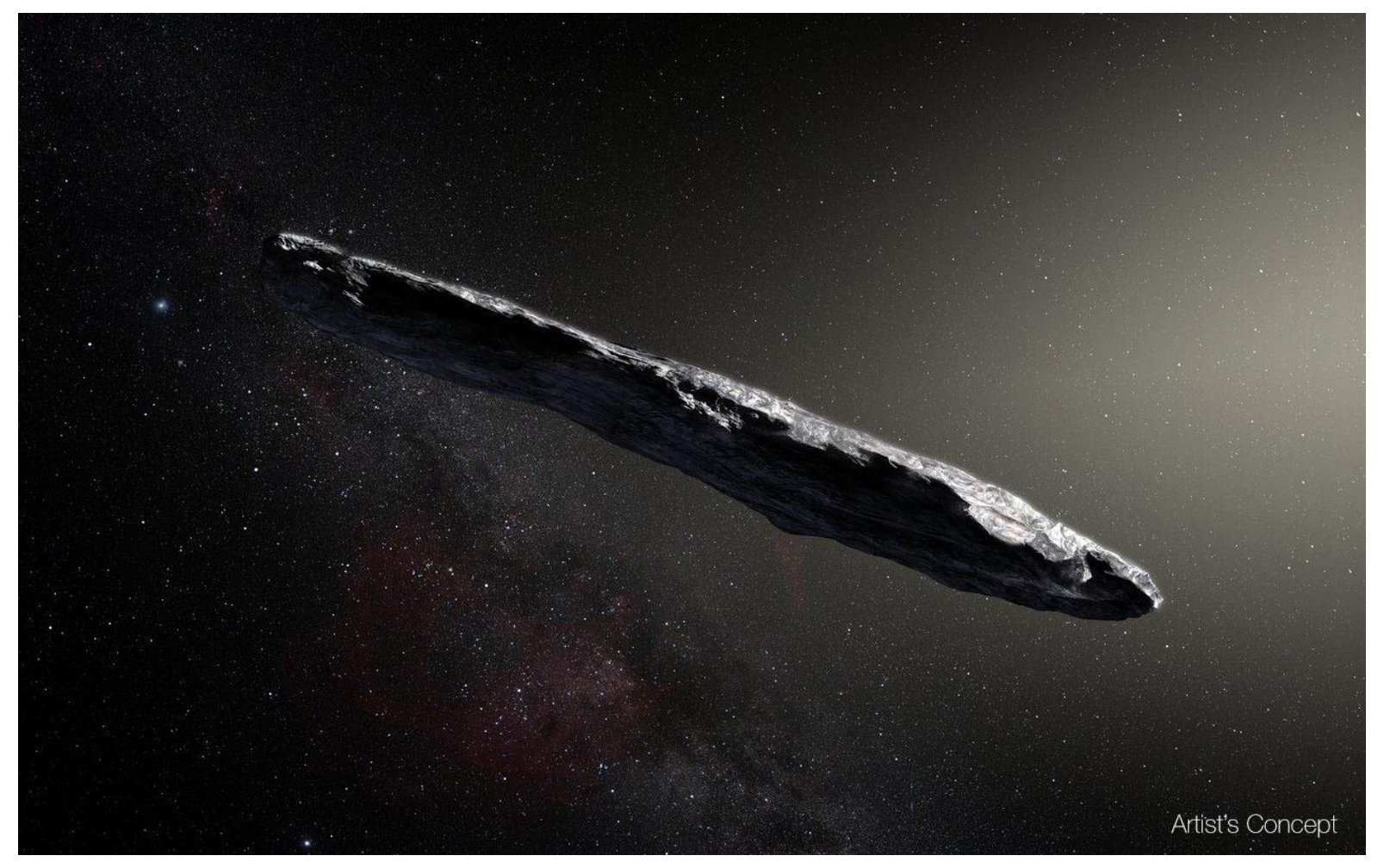
1. White Dwarf Pollution

Between a quarter and half of all white dwarfs observed show evidence of heavy elements closely aligned with terrestrial planet composition in their atmospheres (Koester et al., 2014, Bonsor et al., 2020). The extreme densities of white dwarfs cause these elements to gravitationally settle on fast timescales and disappear from view. So, the material we see must have been recently accreted from a disrupting planetesimal.

Direct observations of two disrupting exo-asteroids have bolstered this idea (Vanderburg et al., 2015, Vanderbosch et al., 2019). The processes which lead to planetesimals breaking up around white dwarfs are still poorly understood and this work aims to further our understanding of this area.

Previous theoretical work has used spherical approximations. However, observations of Solar System asteroids show that they come in a variety of different shapes and sizes (as can be seen in Figure 1) but generally they can be well described by an ellipsoidal model.

Figure 1: Artist's concept of the extremely elongated interstellar asteroid 1I/'Oumuamua Credit: ESO/ M. Kornmesser



2. Ellipsoidal Shape Model

Here we move away from the typical spherical shape model that has been used in previous theoretical work and adopt an ellipsoidal shape.

Ellipsoids can be described by two aspect ratios $\mathfrak{b}$ and $\mathfrak{c}$, which relate the shape's different semi-axes (a, b and c in size order) and give an idea of the degree of elongation of the shape.

$$\mathfrak{b} = \frac{b}{a}$$

$$\mathfrak{c} = \frac{c}{a}$$

For example, a typical asteroid could have $\mathfrak{b} = 0.8$, whereas the interstellar asteroid 'Oumuamua may have $\mathfrak{b} = 0.1$ (Meech et al., 2017)!

We define an ellipsoid as oblate when $\mathfrak{b} = \mathfrak{c}$ and prolate when $\mathfrak{b} = 1$ and use both these definitions here. Click here to open interactive 3D models of each shape used in this work.

3. Analytical Framework

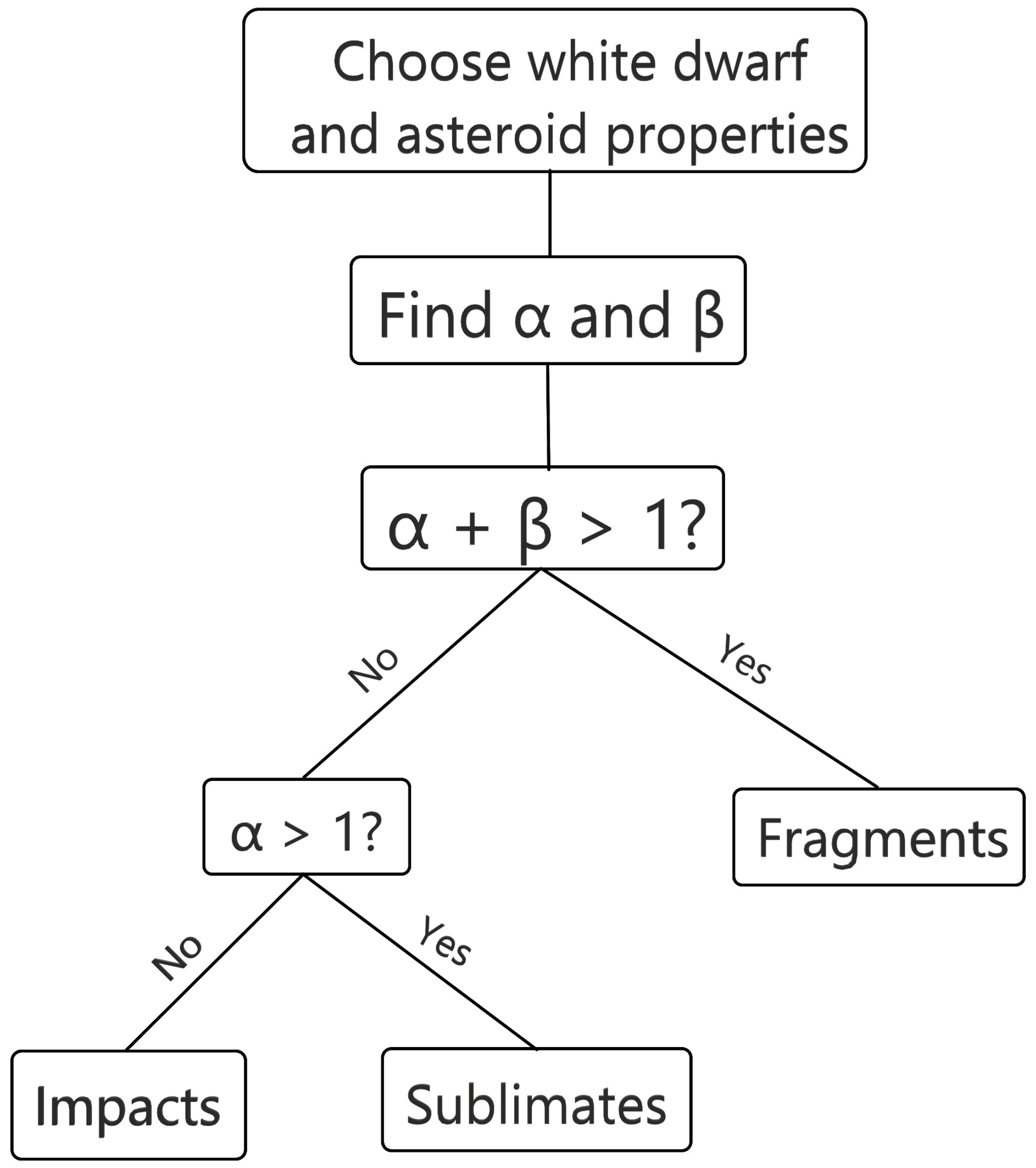
Following a procedure outlined in Brown et al., 2017 for quasi-spherical planetesimals, we developed an analytical model which considers ellipsoidal asteroids approaching a white dwarf on extremely eccentric ($e \sim 1$) orbits. The possible disruption is divided into three outcomes:

- *Sublimation*: incident starlight causes the asteroid to totally sublime,
- *Fragmentation*: tidal forces overcome self-binding forces and the asteroid fragments,
- *Impacts*: the asteroid impacts directly onto the surface of the white dwarf.

The process comes down to identifying two variables for any combination of white dwarf and asteroid properties.

- The *sublimation parameter* α, is the minimum size for a body to survive sublimation alone down to the white dwarf's atmosphere.
- The *binding-size parameter* β, is the threshold size for a body to start fragmenting.

Once these two parameters have been found, they can be run through the following logical flowchart to identify its ultimate mode of destruction.



Choose white dwarf and asteroid properties

Find α and β

α + β > 1?

No

Yes

α > 1?

Fragments

No

Yes

Impacts

Sublimates

Figure 2: Logical flowchart depicting how to identify the destruction mode for any mixture of asteroid and white dwarf properties.

4. Main Belt Analogue

An asteroid belt similar to the Solar System's main belt could survive a star's giant branch evolutionary phase and provide an ample reservoir to pollute white dwarfs.

Here we construct a simplified main belt with the following properties to investigate the expected debris distribution if every asteroid in the belt was randomly perturbed towards the white dwarf:

- 100 asteroids
- Power law size distribution ($n \sim 0.9$ for $a > 1$km and $n \sim 0.26$ for $a < 1$km) (Peña et al., 2020)
- Each asteroid has randomly selected aspect ratios $\mathfrak{b}$ and $\mathfrak{c}$
- Each asteroid has randomly selected material properties (rocky or snowy)

5. Results

We find that utilising the triaxial model makes a significant difference to the results produced using a spherical model. The distance from the white dwarf where destruction occurs can change by orders of magnitude, and in some cases the destruction mode itself can change.

For a 11,000K white dwarf and a cooling age of 0.69Gyr, we run the entire Main Belt analogue through the analytical framework and record the position and mode of their disruption. The results of this simulation are presented below.

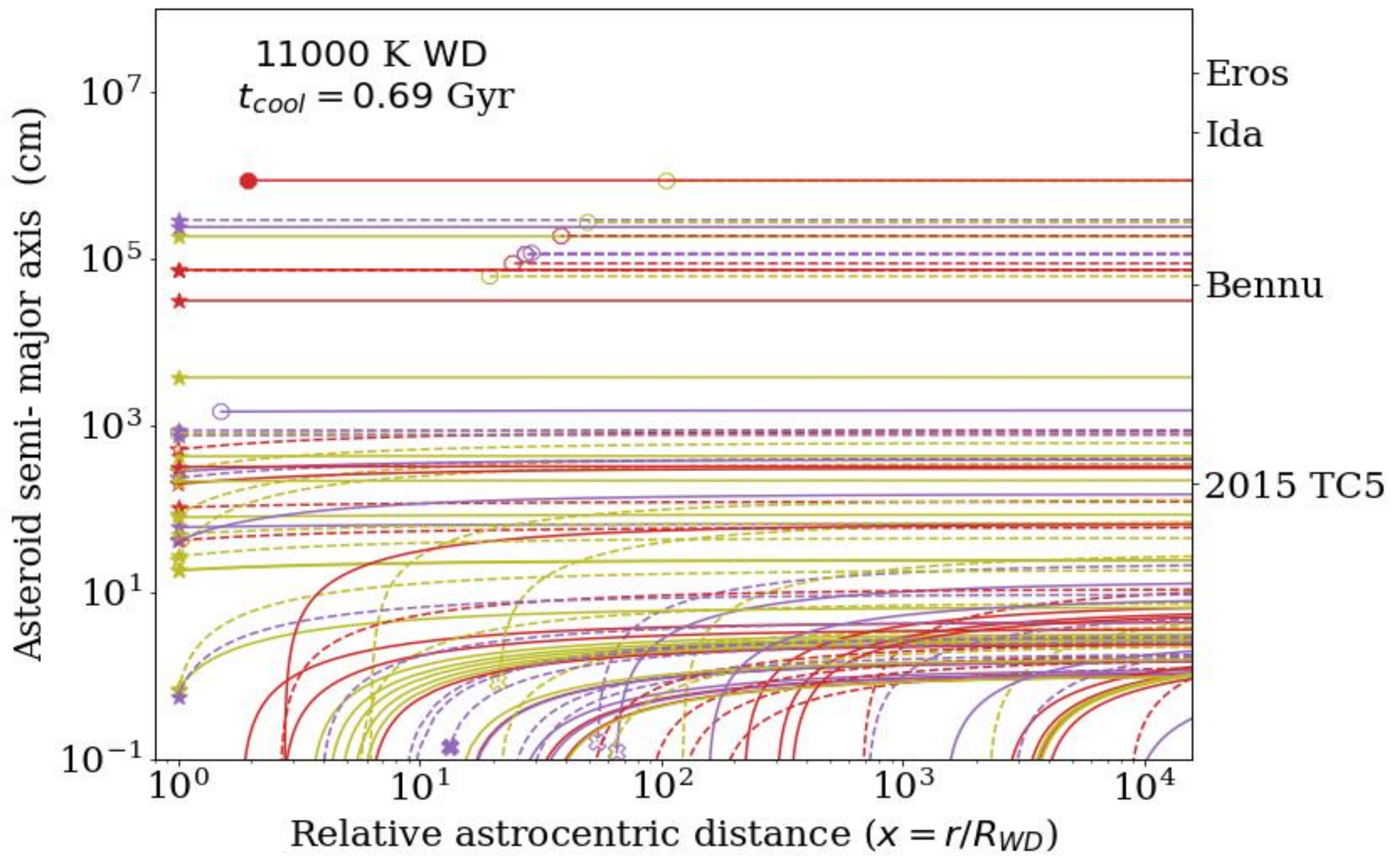


Figure 3: how an asteroid's semi-major axis changes as it approaches a white dwarf. The above legend describes the parameters included. Further, the dotted lines indicate the more extreme shape model has been used.

We find that all three modes of destruction occur. Smaller bodies can sublimate at large distances from the white dwarf. Direct impacts on to the surface of the star occur for a range of asteroid sizes. Fragmentation occurs for larger bodies, with the onset of fragmentation occurring for smaller snowy bodies compared to rocky asteroids.

For rocky asteroids, the different shape models do not affect the disruption outcome. Whereas snowy asteroids with extreme shape models are more susceptible to sublimation at larger sizes than standard shape models.

6. Conclusions

Triaxial shape models provide a more accurate model for asteroids than a spherical model. We can place constraints on where the planetary debris from a disrupted asteroid will orbit. This simple analytical formulism can be used in other studies to predict the destruction regime of specific asteroids.

Further work on this project intends to include the effect of rotation and to follow the evolution of the fragmentation products.

We invite feedback and the opportunity to collaborate in furthering this work.

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Background image: "NGC 247" NASA/ESA