Towards a Population Synthesis Model of Objects Formed By Self-Gravitating Disc Fragmentation and Tidal Downsizing

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Abstract

We present a simple population synthesis model (the first of its kind) for creating planets and brown dwarfs via self-gravitating disc fragmentation and tidal downsizing (TD). We combine i) a 1D self-gravitating disc model, ii) analytic calculations to describe the fragmentation process, and iii) a semi-analytic model of fragment evolution. **The population of solid grains in each fragment is evolved** through growth and sedimentation, evaporation and potential formation of a solid core. **Simultaneously, the fragment migrates through the disc, and can be tidally disrupted.** There are still key pieces of physics missing from the model, but we present it as a step in the right direction, towards a mature population synthesis model to compare and contrast with the models that already exist for the core accretion paradigm.

We find in general that despite the possibility of forming terrestrial planets via TD, this is a rare event, and generally speaking, brown dwarfs and giant planets dominate the final population of objects formed by this process.

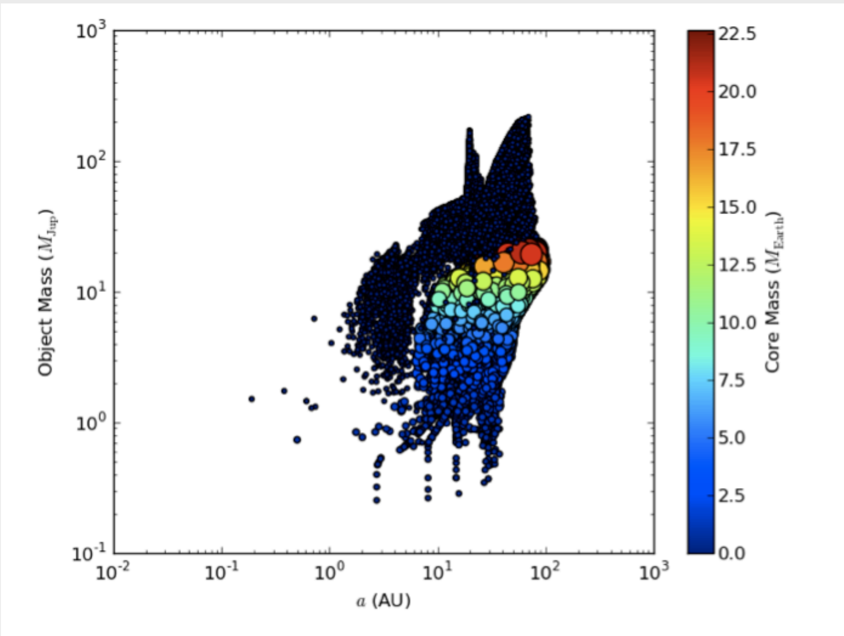
Introduction

Population synthesis modelling has been an important tool in refining the core accretion theory of planet formation (e.g. Ida & Lin 2008, Mordasini et al 2012). Gravitational instability theory does not possess an equivalent tool. Without this, we cannot say quantitatively to what extent this formation mode will leave an imprint on, say, the statistical properties of the observed exoplanets.

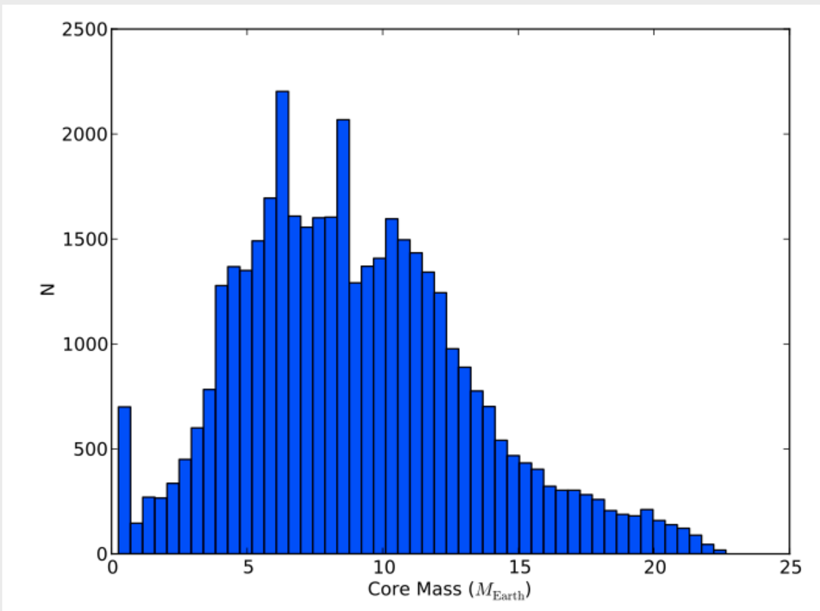
Tidal downsizing theory (TD) (Boley et al 2010, 2011, Nayakshin 2010a,b, 2011) has recently described the subsequent evolution of self-gravitating disc fragments into (potentially) low-mass objects, at low semi-major axis. But how frequently? Population synthesis is needed more than ever to answer this question.

Results

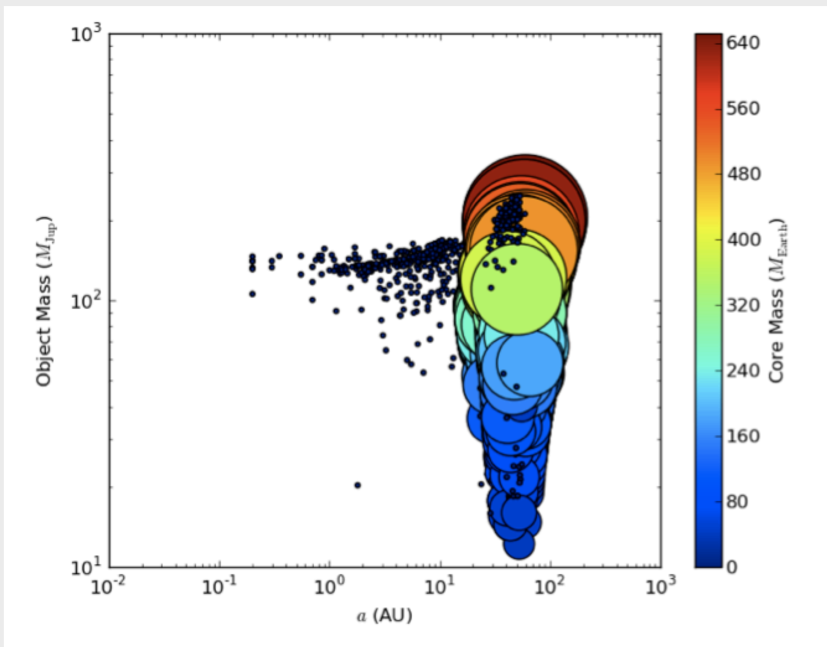
We run the model four times, producing over a million disc fragments. We change the **relationship between temperature and opacity** inside the fragment and the **strength of disc migration**. Alongside these, we also investigate the issue of **disc truncation** during the fragmentation process. For three of the runs, we assume that the disc has an initial radius $\mathbf{r}_{\mathbf{max}}$ larger than that of the 1D model (where $\mathbf{r}_{\mathbf{out}}$ = 50 AU), and the disc is truncated by fragmentation. In the fourth, we run a separate set of disc models with a fixed ($\mathbf{r}_{\mathbf{out}}$ = 100 AU), and assume no truncation occurs after fragmentation.



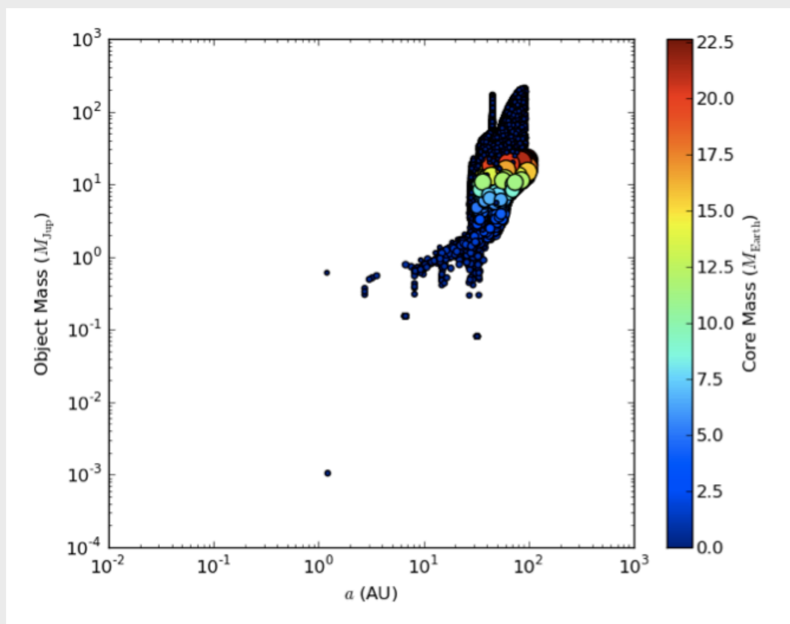
Standard Run



Core Masses in the Standard Run

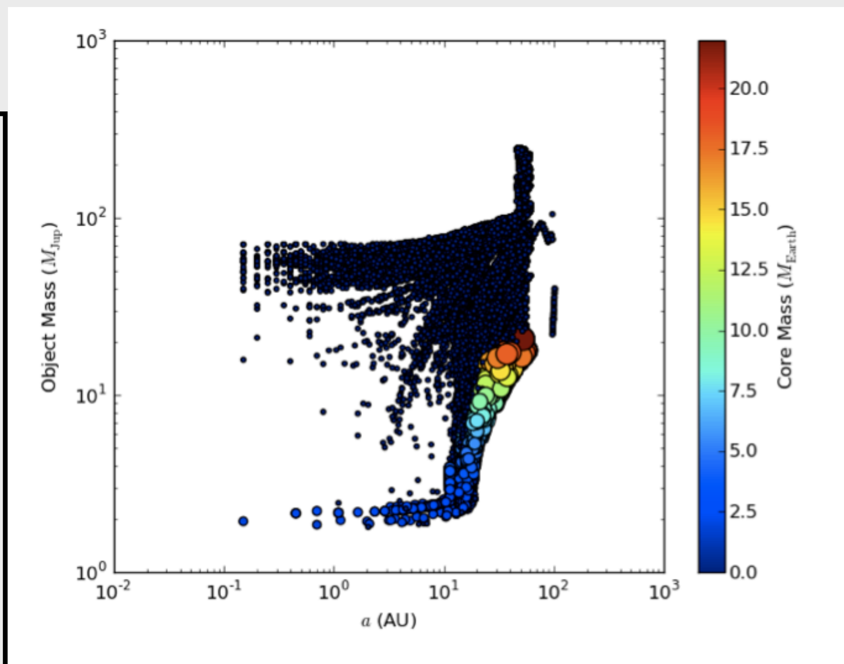


Opacity Law Change
(Clearly problematic!)



Slow Migration

Typically, around **forty percent of all fragments are completely destroyed**. Of the remaining fragments, around half are brown dwarfs, and the rest are giant planets with or without solid cores. **Out of a million fragments, only one fragment evolved to become a terrestrial-type object.**



No Disc Truncation

Conclusions

Despite the action of tidal downsizing, the gravitational instability tends to form massive objects at large semimajor axis. The rate of fragment destruction is substantial, which may help explain eruptive phenomena such as FU Ori events (e.g. Dunham & Vorobyov 2012). We saw some weak evidence of processed grains being returned to the disc after disruption. This points to required future improvements in the model, alongside improved treatment of opacity evolution, planetesimal capture, fragment migration, and the evolution of fragment angular momentum.

References

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The Model

The population synthesis model has three components:

i) **a 1D self-gravitating disc model** (e.g. Pringle 1981, Rice and Armitage 2009) which describes the evolution of the disc's surface density and temperature as it evolves via the gravitational instability and X-ray photoevaporation (Owen et al 2011). By varying the star mass, disc mass and X-Ray luminosity, we produce a suite of disc models, with disc lifetimes consistent with observations (Haisch et al 2001). These disc models allow us to identify where disc fragments may form using:

ii) **analytic calculations for disc fragmentation** (Forgan & Rice 2011). These calculations find locations in the disc where the local Jeans mass inside a spiral arm is rapidly decreasing, and are therefore prone to fragmentation. The initial conditions of the disc models are used to produce disc fragments, with mass equal to the local Jeans mass, with a fragment spacing of 1.5 to 3 Hill Radii. These fragments are then evolved using:

iii) **A semi-analytic model of fragment evolution** (Nayakshin 2010a,b,2011) which describes the evolution of the gas and solid components of the fragment. This includes growth of the grain population, sedimentation towards the centre of the fragment, production of a solid core, evaporation of dust, migration of the embryo and tidal disruption.

The timescales on which each physical process operates governs the fate of the disc fragment.

Producing a core rapidly before disruption can produce terrestrial planets or giant planets with solid cores. Fragments that are disrupted before core formation can deliver planetesimal belts to the protostellar disc (Nayakshin & Cha 2012). Fragments that reach the dust evaporation temperature quickly will produce either gas giants without cores or brown dwarfs.