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Full-lifetime simulations of multiple planets across all phases of stellar evolution

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Abstract

We know that planetary systems are just as common around white dwarfs as around main-sequence stars. However, self-consistently linking a planetary system across these two phases of stellar evolution through the violent giant branch poses computational challenges, and previous studies restricted architectures to equal-mass planets. Here, we remove this constraint and perform over 450 numerical integrations over a Hubble time (14 Gyr) of packed planetary systems with unequal-mass planets. We characterize the resulting trends as a function of planet order and mass. We find that intrusive radial incursions in the vicinity of the white dwarf become less likely as the dispersion amongst planet masses increases. The orbital meandering which may sustain a sufficiently dynamic environment around a white dwarf to explain observations is more dependent on the presence of terrestrial-mass planets than any variation in planetary mass. Triggering unpacking or instability during the white dwarf phase is comparably easy for systems of unequal-mass planets and systems of equal-mass planets; instabilities during the giant branch phase remain rare and require fine-tuning of initial conditions. We list the key dynamical features of each simulation individually (in [1]) as a potential guide for upcoming discoveries.

1. Introduction

Up until now full-lifetime simulations of multi-planet systems have been restricted to equal-mass planets. Although this assumption significantly helps constrain the available parameter space to explore, real systems exhibit a variance of planetary masses of a few per cent to many orders of magnitude. Further, previous studies have predominately modelled Jupiter-mass planets, which are rarer than terrestrial planets. Further, no published study has simulated multiple planets with test particles.

Here, we break these barriers, and perform a suite of 14 Gyr simulations of unequal-mass planets, occasionally including test particles, in order to explore the consequences and resulting trends.

2. Figures

Simulations of planetary systems through multiple stages of stellar evolution require both the star and planets to be treated self-consistently as a function of time. We use an existing code which combines planetary (MERCURY) and stellar (SSE) evolution.

The output from SSE was ported directly into a heavily modified version of the MERCURY planetary evolution code. Our version of MERCURY used the Bulirsch–Stoer integrator throughout the simulation, ensuring accurate treatment of potential close encounters. We adopted a tolerance value of 10^{-12}. Stellar mass and radius changes were interpolated within each Bulirsch–Stoer timestep, helping to ensure accuracy. Stars which engulfed planets throughout the course of the simulations had masses which were increased accordingly. Our output frequency was 1 Myr; a shorter frequency would have prohibitively slowed down our simulations. As is the MERCURY default, any collisions between planets were treated as purely inelastic. Further, our modified code allowed for the tracking of the minimum orbital pericentre of all surviving planets.

Figs. 1-2 illustrate examples of two different full-lifetime simulations, and Fig. 3 illustrates the cumulative statistics for test particles which are engulfed in the white dwarf, across all simulations.

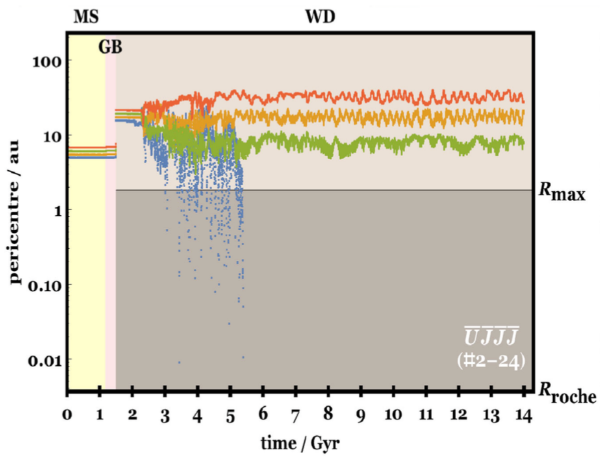

Figure 1: The full-lifetime evolution of four terrestrial planets such that the innermost one is about 5% of the mass of the outer three. The least massive planet is eventually scattered towards the white dwarf.

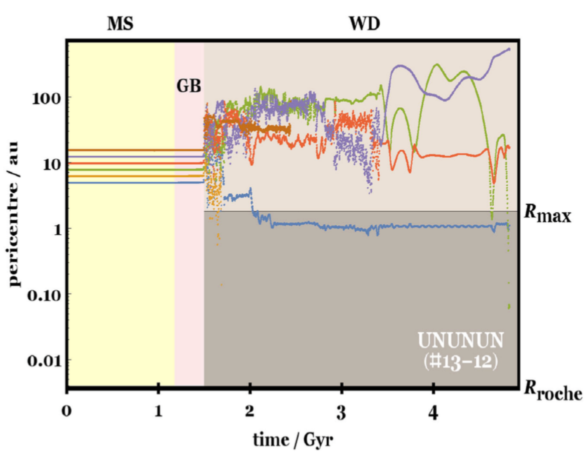

Figure 2: Evolution over 5 Gyr of six planets, three of which are Uranus-mass and three of which are Neptune-mass. Unpacking of the system occurs almost immediately after the giant branch phase.

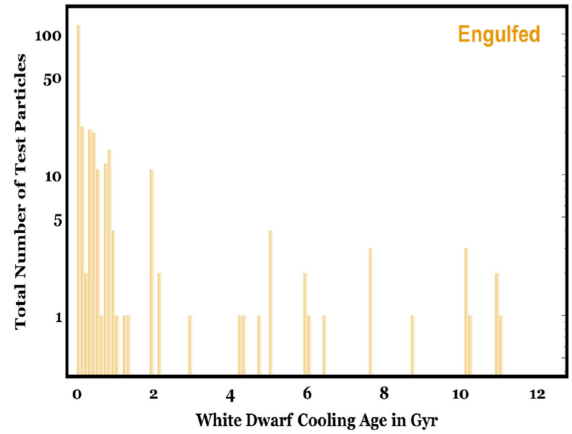

Figure 3: The white dwarf cooling age (time since becoming a white dwarf) at which test particles across all simulations entered the white dwarf Roche, or disruption, radius. The histograms illustrate the pollution decay rate obtained from the simulations.

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[1] Veras, D., Mustill, A.J., Gänsicke, B.T., Redfield, S., Georgakarakos, N., Bowler, A.B. and Lloyd, M.J.S.: Full-lifetime simulations of multiple unequal-mass planets across all phases of stellar evolution, MNRAS, Vol. 458, 3942-3967, 2016.