EPSC Abstracts
Vol. 8, EPSC2013-36, 2013
European Planetary Science Congress 2013

The Fate of Exoplanetary Systems and the Implications for White Dwarf Pollution

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Abstract

Mounting discoveries of extrasolar planets orbiting post-main-sequence stars motivate studies to understand the fate of these planets. Also, polluted white dwarfs (WDs) likely represent dynamically active systems at late times. Here, we perform full-lifetime simulations of one-, two- and three-planet systems from the endpoint of formation to several Gyr into the WD phase of the host star. We outline the physical and computational processes which must be considered for post-main-sequence planetary studies, and characterize the challenges in explaining the robust observational signatures of infrared excess in white dwarfs by appealing to late-stage planetary systems.

1. Introduction

Understanding the formation and subsequent dynamical evolution of exoplanets has been a motivational hallmark for many observational and theoretical investigations. However, extrasolar planets continue to be discovered in surprising and exotic environments, and questions about the endstate of exoplanets are becoming increasingly relevant. Few studies so far have modeled these systems, which often feature evolved and variable parent stars. The rich dynamics therein fundamentally differ from studies of planets around main sequence stars.

The importance of modeling post main-sequence systems is highlighted by observations of planets orbiting sub-giant, red giant branch, and horizontal branch stars, as well as WDs whose atmospheres are clearly polluted. Observed signatures of metal pollution in WDs, which occurs in around 25 per cent of DA WDs [9], are generally consistent with the accretion of rocky asteroids.

In order for a WD to be polluted by material from an outer planetary system, comets, asteroids or planets must be scattered at least close enough to the star (at about one Solar radius) so that they are tidally disrupted. Changes to the dynamics of the planetary system following stellar mass loss has been suggested as a potential cause of increased numbers of planetary bodies scattered onto star-grazing orbits [1, 2]. Even in planetary systems where the planets remain on stable orbits, [1] and [2] show that sufficiently many asteroids or comets can be scattered onto stargrazing orbits to explain some of the observations of polluted WDs. Instabilities in planetary systems could provide a potential explanation for pollution in these, and other, WDs.

2. Orbital Evolution

The equations of motion describing the evolution of one planet due to isotropic stellar mass loss can be expressed in closed form as [6]:

$$\frac{da}{dt} = -\frac{a\left(1+e^2+2e\cos f\right)}{1-e^2}\frac{1}{\mu}\frac{d\mu}{dt} \quad (1)$$

$$\frac{de}{dt} = -\left(e+\cos f\right)\frac{1}{\mu}\frac{d\mu}{dt} \quad (2)$$

$$\frac{di}{dt} = \frac{d\Omega}{dt} = 0 \quad (3)$$

$$\frac{d\omega}{dt} = \frac{d\varpi}{dt} = -\frac{\sin f}{e}\frac{1}{\mu}\frac{d\mu}{dt} \quad (4)$$

$$\frac{df}{dt} = -\frac{d\varpi}{dt} + \frac{n\left(1+e\cos f\right)^2}{\left(1-e^2\right)^{3/2}} \quad (5)$$

where a represents the semimajor axis, e the eccentricity, i the inclination, ω the argument of pericentre, ϖ the longitude of pericentre, Ω the longitude of ascending node, f the true anomaly and n the mean motion. Here, $\mu = G(M_{\rm star} + M_{\rm planet})$, where M represents mass. If the amount of mass lost and mass loss rate are small and the orbit is tight, then the orbit will expand but maintain its eccentricity. Otherwise, however, the eccentricity can increase or decrease. We show that the isotropic mass loss assumption is a robust approximation to use when considering planetary evolution in real systems [7].

For two- and three-planet systems, numerical simulations are required to model both the consequences of mass loss and the mutual interactions between the planets. In order to conduct the simulations, we merge a stellar evolution code with a planetary dynamics code. We use the Bulirsch-Stoer integrator, and interpolate the stellar code's stellar mass output between each planetary code timestep. We consider stars with progenitor masses of $3M_{\odot}$, $4M_{\odot}$, $5M_{\odot}$, $6M_{\odot}$, $7M_{\odot}$ and $8M_{\odot}$.

We compare the instabilities that arise from 2-planet simulations during the WD phase [8] with an observed sample of polluted WDs [3, 4] in Figure 1. Both the observations and simulations show a broad consensus. The result of 3-planet simulations [5] also demonstrates good agreement.

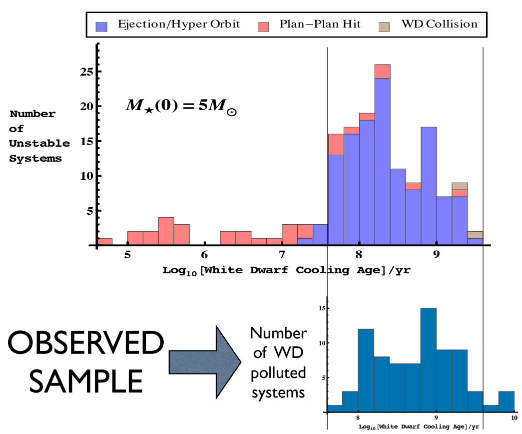

Figure 1: Comparison of planetary simulations from [8] showcasing instability during the WD phase and an observed sample of 78 observed WDs from [3] and [4]. The WD cooling ages in both plots are similar.

3. Conclusions

We have performed long-term (5 Gyr) simulations that consistently treat the dynamics of systems with one, two and three massive planets and every phase of stellar evolution for a wide range of progenitor stellar masses. These computationally demanding simulations suggest that stable main sequence systems are in danger of future instability, and may provide a route for explaining the asteroid delivery mechanism in observed polluted white dwarf systems.

Acknowledgements

This work made use of facilities funded by the European Union through ERC grant number 279973.

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