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Origin of debris disks and the supply of metals in DZ white dwarfs

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Abstract. We discuss the dynamical evolution of minor planetary bodies in the outer regions of planetary systems around the progenitors of DZ white dwarfs. We show that during the planetary-nebula phase of these stars, mass loss can lead to the expansion of all planetary bodies. The orbital eccentricity of the minor bodies, as relics of planetesimals, may be largely excited by the perturbation due to both gas drag effects and nearby gas giant planets. Some of these bodies migrate toward the host star, while others are scattered out of the planetary system. The former have modest probability of being captured by the sweeping secular resonances of giant planets, and induced to migrate toward the host star. When they venture close to their host stars, their orbits are tidally circularized so that they form compact disks where they may undergo further collisionally driven evolution. During the subsequent post main sequence evolution of their host stars, this process may provide an avenue which continually channels heavy elements onto the surface of the white dwarfs. We suggest that this scenario provides an explanation for the recently discovered Calcium line variation in G29-38.

Keywords. Giant planet, debris disks, planet dynamic, n-body simulations, white dwarfs

1. Introduction

In the recent years, more than 200 planets have been found around solar-type stars. Despite these impressive gains, observational selection effects limit the discovery space to only a small fraction of all potential orbital configurations.

An effective method to find indirect evidence for the presence of planets is to search for remnant of planetary system in post-main sequence stars. Debris disks have been detected around a few white dwarfs with the highest photospheric metal abundances, such as G29-38 (Heppel & Thompson 2007), and they are generally considered to represent the relics of planet building process. All of them are metal-rich, with substantial abundances of photospheric Calcium and Silicates and show no signs of H or He. (Koester *et al.* 1997)

A survey of DA white dwarfs reveals 25% of white dwarfs have excess metals in their atmosphere (Zuckerman *et al.* 2003). This excess is unexpected due to their short estimated gravitational settling time scales ($10^{-2} \sim 10^{6}$ years; Dupuis et al. 1992; comparison with the typical ages of these white dwarfs ($10^{8} \sim 10^{9}$ years). This dichotomy suggest that these metal contents may be continually replenished. One class of possible reservoir is debris disks in the proximity of these white dwarfs. The inferred detection of a debris disk at $0.14 \sim 1\ R_{\odot}$, within the tidal disruption radius of the white dwarf (Jura 2003) provides support for this scenario.

During planetary nebula phase, the stellar envelopes extend to several AU's. Any planets and residual planetesimals within this region would encounter a strong hydrodynamic drag and undergo orbital decay. Outside the red giants' envelope, planetary orbits expand due to stellar mass losses. Residual planetesimals also experience hydrodynamic drag induced by the stellar wind as well as the dynamical perturbation due to any neighboring gas giant planets.

In this paper, our goal is to examine the dynamic evolution of outer planets and planetesimals, which may have once resided in regions similar to the asteroid or the Kuiper belt regions. We show that they may be scattered to the stellar proximity and form the disks around DZ white dwarfs. We find that the orbits of the residual planetesimals are destablished by the planetary perturbations during the mass loss of their host stars.

2. A working model

We assume the planetary system is composed of three populations of objects, including the host star, several gas giant planets, and a large number of planetesimals.

The model of planetary system we used is analogous to the solar system. We consider the main sequence progenitors of the DZ white dwarfs to have masses in the range of $2\,M_\odot < M_* < 4\,M_\odot$ (A-F stars). We assume the mass of the white dwarf is $\sim 0.5\,M_\odot$, which is common for the remnant white dwarf of such stars. During the mass loss, we assume the mass of star changes linearly with time. Beyond the stellar envelope during the red giant phase ($\sim$ a few AUs), planets' orbits expand with the stellar mass loss. The region within $\sim 10^2$ AU is essentially depleted (see contribution by Dong *et al.* in this volume).

In addition to the expansion of the planets' and planetesimals' orbits, the ratio of their mass to that of their host stars increases. Consequently their Roche lobes occupies a greater fraction of their newly acquired semi major axis. This change leads to an enhanced planetary perturbation which destabilizes the orbits of residual planetesimals.

In order to demonstrate this effect, we carry out a series of simulations with 100 planetesimals. The initial separation between these small bodies varies between $0.01 \sim 1$ AU. We choose a median semi-major axis at 350 AU. We also include two planets which have a asymptotic (at the end of stellar mass-loss epoch) semi major axis 50 and 100 AU and mass $\sim 10^{-6} M_\odot$. Such kind of planets are analogous to Earth-like planets which may have formed at a few AU and undergone adiabatic orbital expansion during the stellar mass loss. Additional and more massive planets may be present around some other planetary systems, but the physical process we intend to study is similar. The initial eccentricities and inclinations of planets and planetesimals are all set to be zero. Although the mass of the planets are relatively small, planetesimals can be efficiently scattered when their eccentricities are excited and their orbits cross those of planets.

To determine the dynamic evolution of the system, we neglected the interaction between small planetesimals. Therefore, the planetesimals generally move in a central gravitational field, with the perturbation of of the giant planets. In a non-rotating frame centered on the star, the equation of motion can be expressed as:

$$\frac{d^2\mathbf{r}_i}{dt^2} = -\frac{GM_*\mathbf{r}_i}{r_i^3} - \Sigma_j \frac{GM_j(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r_j}|^3} - \Sigma_j \frac{GM_j\mathbf{r}_j}{r_j^3} \tag{2.1}$$

where M_* and M_j are the mass of the central star and that of the planets, respectively. $\mathbf{r}_i$ and $\mathbf{r}_j$ are the position of a particular planetesimal and planets. The perturbation term in equation (2.1) is normally small. However, the effect of small perturbation force can accumulate with time.

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3. Scenarios and simulations

Enhancement of dynamical instability. As the semi-major axis of planets changes proportionally to their mass of host star, the mass ratios of the planets μ increases with time, and the the scaled separation k of the planetesimals decreases simultaneously. Here μ and k are defined as

$$\mu(t) = \frac{M_p}{M_*(t)} \tag{3.1a}$$

$$k(t) = \frac{a_{i+1}(t) - a_i(t)}{R_H(t)} \tag{3.1b}$$

where a_i is the separation of the planetesimals, and R_H is the Hill's radius. Using the empirical fitting formula (Zhou, Lin & Sun 2007), for the time scale for orbit crossing,

$$\begin{aligned} log\left(\frac{T_c}{yr}\right) &= A + Blog\left(\frac{k_0}{2.3}\right) \\ A &= -2 - 0.27log(\mu) \\ B &= 18.7 + 1.1log(\mu) \end{aligned} \tag{3.2}$$

we find that for planetesimals in systems with initial $k_0 = 20$, can survive the planets' perturbation during the main sequence evolution of their host stars. The magnitude of the orbit-crossing time scale T_c can decrease from 10^{10} years to 10^8 years during their host stars' mass loss. On the other hand, the period of giant planets T_p increases proportional to $M_*^{-1.5}$ due to the Keplerian motion. Both of these two factors enhances the tendency toward dynamical instability of the system. In this process, the eccentricity of planetesimals is exited, but the orbits of planets expand adiabatically, which leads to the orbit crossing of planetesimals and planets.

Migration toward host star. If two or more planets survive the mass loss scenery, they would scatter the nearby planetesimals, after orbit crossing. As the eccentricity of planetesimals can be greatly excited and their semi-major axis remain largely unaffected, a fraction of them can venture into the inner region within 100 AU from the host star. Using a Hermit integrator kindly provide by Dr. Sverre Aarseth, we simulate these scattering events. Our results show that the course of the scattering can last for a long time. If the initial separation between planetesimals is 0.5 AU and the initial eccentricity is 0.7, $\sim 25\%$ of the planetesimals would become unbounded in 5 million years. This timescale becomes smaller if the mass of the planets, the initial eccentricity of planetesimals, or the initial semi-major axis is larger.

Eccentricity of planetesimals can be excited to magnitudes close to unity, but the semi-major axis can either increase or decrease. A fraction of planetesimals migrate toward the host star, as their semi-major axis becomes smaller and the orbits of them no longer cross those of the planets, which makes their final orbits stable. The final periastron can be well within 30 AU from the host star. For other planetesimals, eccentricity may exceed unity and they are scattered out of the system. Such objects may become a source of freely floating rocky planets and gas giants. (Lucas & Roche 2000) Result of our simulation shows that only ~ 5 of the planetesimals can migrate into the inner region.

Secular resonance. During $10^8 \sim 10^9$ years, as planets are immersed in numerous, low-mass planetesimals, their orbits migrate slowly and their secular resonances sweep across a wide region, analogous to the late heavy bombardment scenario (Gomes *et al.* 2005). Duncan *et al.* (2007) point out that a planet embedded near 20 AU in an initially low eccentricity minimum-mass planetesimal disk typically migrates 1 AU in 10^4 years, and the ratio of semi-major axis of different planets changes after migration. Considering the time scale of DZ white dwarfs, the migration rate should be much slower, which means the density of planetesimals disk would be lower than typical density in Duncan's work.

When planetesimals are captured by secular resonant point of planets, their eccentricity would be exited while semi-major axis remains unchanged. This tendency brings their periastron close to their host star. As secular resonance depends mainly on the ratio of planets' semi-major axis, planetesimals in different regions migrate to the host star due to secular resonance. This process could continuously provide materials to the disks around white dwarfs. At the proximity of their host stars, intense tidal force disrupt the planetesimals and their debris form debris disks and supply heavy elements to the atmosphere of white dwarfs, such as G29-38.

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