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Origin of the dusty disks around white dwarfs

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Abstract. Some circumstantial evidence for residual planetesimals is constructed based on the recent discovery of a dusty ring around a young white dwarf at the center of the Helix nebula (Su *et al.* 2007). This ring extends between about 35 and 150 AU from the nebula center, and have a total mass of about 0.13 $M_\oplus$. In this paper we propose that this ring is the by-product of planets and planetesimals' orbital evolution during the epoch when the central star rapidly lost most of its mass. We examine the dynamical evolution of planetary systems similar to the solar system (*i.e.* with gas giant planets and residual planetesimals) as their host stars evolve off the main sequence. During the process, some planetesimals will be captured by the gas giants into mean motion resonances and their mutual collisions will form a dust ring similar to that observed at the center of the Helix nebula.

Keywords. Giant planet; planetary formation; debris disks; planet dynamics; n-body simulation

1. The dynamical model

We idealize the dynamics of the system into a series of interaction between three populations of objects: planetesimals with mass m_j, planets with mass M_j, and a central star with mass M_*.

There are two mean factors which influence the orbital change of a planet around the central star during the epoch of its mass loss: the change of the star's mass, which reduces its gravity and causes the planet's orbit to expand; and the gas drag by the outflow, which induces orbital decay. Even though the magnitude of the gas drag on a giant planet is negligible, it has a significant effect on the orbit of the planetesimals, which are also perturbed by the gravity of the planet.

But the drag effect has a significant effect on the orbit of the planetesimal. In addition, it is also perturbed by the gravity of the planet. In a non rotating frame centered on the star, the equation of motion of a planetesimal at a position $\mathbf{r}$ can be expressed as

$$\frac{d^2\mathbf{r}_i}{dt^2} = -\frac{GM_*\mathbf{r}_i}{r_i^3} - \Sigma_j \frac{GM_j(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r_j}|^3} - \Sigma_j \frac{GM_j\mathbf{r}_j}{r_j^3} - \frac{\mathbf{f}_i}{m} \tag{1.1}$$

where $\mathbf{r}_i$ is the position of the planetesimal, $\mathbf{r}_j$ is the position of the planet and M_* is a function of time. The magnitude of the drag force on a planetesimal by the wind of its host star can be expressed as

$$\mathbf{f}_i = \pi\rho_g(\dot{\mathbf{r}}_\mathbf{i} - \mathbf{v_g})|\dot{\mathbf{r}}_\mathbf{i} - \mathbf{v_g}|(\mathbf{s^2} + \mathbf{s_c^2}). \tag{1.2}$$

where v_g is the wind velocity, $s = (3m_i/4\pi\rho_p)^{1/3}$ and $s_c = Gm_i/v_p^2$ are the physical and gravitational radius of a planetesimal with a mass m and density ρ_p. In the radial direction, this drag contribution is much smaller than the gravity from all three bodies. However, in the azimuthal direction, the drag slows down the planetesimals' orbit and induces them to migrate inward. The density of the background gas is determined by the stellar mass loss rate

$$\dot{M}_* = 4\pi R^2 \rho_g v_g \tag{1.3}$$

The equation of motion is solved with a Hermit scheme which is kindly provided by Dr Sverre Aarseth.

2. Simulations of orbital evolutions and collisions between planets and planetesimals

Simulations based on the dynamical model above show there are three types of orbital evolution of planets and planetesimals during the mass lose phase of the red giant progenitor. Regarding the initial conditions of the simulations, we mostly consider a star with a main-sequence mass in the range $2M_\odot < M_* < 4M_\odot$ (A-F stars). thought to be the progenitor of the $\sim 0.5M_\odot$ white dwarf at the center of the Helix nebula. The analysis to be presented below is particularly relevant for the planetary nebula phase when the typical mass loss rate is $\dot{M}_* \sim 10^{-4} M_\odot$ yr^{-1}. The typical outflow speed is ~ 10 km s^{-1} and $\dot{M}_*$ may vary on the time scale of 10^4 yr.

Results of our simulations show that the orbits of the gas giant planets and super-km-size planetesimals expand adiabatically. The gas drag is insignificant in their orbital evolutions, so their semi major axis are in inverse ratio with the mass of central star. On the other hand, if a planetesimal is smaller than a critical size (about 10 m in our simulation), orbital decay will be introduced due to gas drag; this reduced the particle's angular momentum resulting in a non-adiabatic orbital evolution that makes the particle migrate toward the central star.

Massive planets affect the orbital evolution of intermediate-size planetesimals via trapping at mean motion resonances, where the period of the planetesimal and the period of the planet are in a ratio of two integer numbers. The final orbital semi-major axis of the captured particles does not depend on their initial positions. These intermediate-size planetesimals also acquire modest eccentricities around 0.2, which are determined by the mass of the perturbing planet and the stellar mass loss rate.

When the mass loss rate eventually decreases, a large number of planetesimals would be swept from various starting orbits into several mean motion resonances (usually two or three), with am modest eccentricity. Collisions between them would take place and a dust ring would form. For example, a 100 $M_\oplus$ planetesimal belt with objects 100 m in size, located between 50–150 AU around a 0.58 $M_\odot$ star, results in a collision frequency of 10^{-8} per year. During 10^5 years, the probability of collision for a given planetesimal is 10^{-3}, resulting in the formation of a dust cloud 0.1 $M_\oplus$ in mass, similar to that observed around the Helix nebula.

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