

A power-law decay evolution scenario for polluted single white dwarfs.

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Introduction White dwarf stars (WDs) are the final evolution stage of main sequence stars with masses less than about 8 solar masses[1]. During the post main sequence evolution, the envelope of such a main sequence star will expand to several AU, therefore planets in the inner region might be swallowed, while the orbits of outer planets would expand due to stellar mass loss[2]. Thus the study of environment around WDs can reveal the structure of exoplanet systems around the progenitor stars.

Recent observations show that 1%-4% of single white dwarfs are accompanied by dusty disks, while the occurrence rate of metal pollution is about 25%-50%. The dusty disks and metal pollution have been associated with accretion of remanent planetary systems around white dwarfs[3,4], yet the dynamical evolution of these two phenomena is still unclear. The physical mechanisms that cause the difference between the two phenomena is well-understood, either.

Result We collect an observational sample of metal-polluted WDs from literatures based on the Montreal-White Dwarf Database (MWDD)[5]. Our sample consists of 47 hydrogen-atmosphere (DA) and 799 helium-atmosphere (non-DA) WDs. By analyzing the observational sample, we find that the mass accretion rate onto the white dwarf generally follows a broken power law decay (Figure 1). Combining with theoretical calculations as well as dynamical simulations, we find that such an observational power law decay matches well with the theoretical prediction, if assuming dust accretion is primarily driven by Poynting-Robertson (PR) drag[6] and the dust source is primarily delivered via dynamically falling asteroids perturbed by a Jovian planet (Figure 2). Furthermore, the turnoff time of the broken power law is just sitting at the timescale $t_{\text{cool}} = 0.68^{+0.35}_{-0.20}$ Gyr, within which most dusty disks are found.

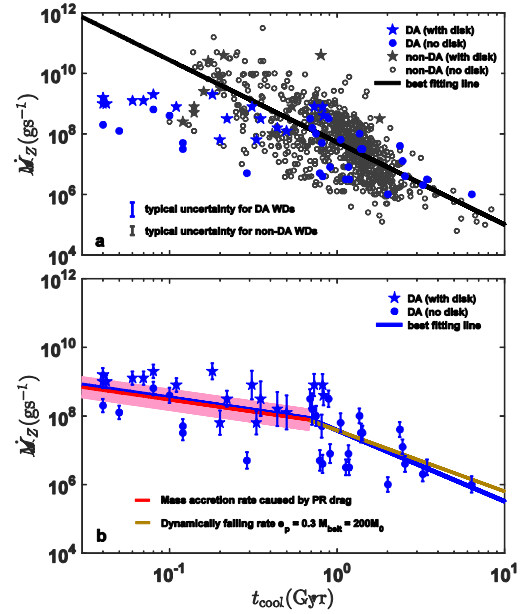


Figure 1: The power law relationship derived from the observational data. a. The accretion rate \dot{M}_Z is plotted as a function of cooling age t_{cool} for the whole sample. The solid black line denotes the best fitting line of \dot{M}_Z and t_{cool} . The typical (median) uncertainties in \dot{M}_Z for DA subsample (blue) and non-DA subsample (grey) are shown in the bottom left corner of the panel. b. \dot{M}_Z is plotted as a function of t_{cool} for the DA subsample. The best fit for the DA subsample (blue solid line) is a broken power law, which matches well with the accretion rate caused by PR (red region for 1σ range and solid red line for a typical case) followed by the dynamically falling rate (solid brown line) of a typical case with a planet eccentricity of 0.3 and asteroid belt mass of 200 times the main asteroid belt.

The above match between observation and theory motivates us to outline the following evolution scenario, with the essence illustrated in Figure 3..

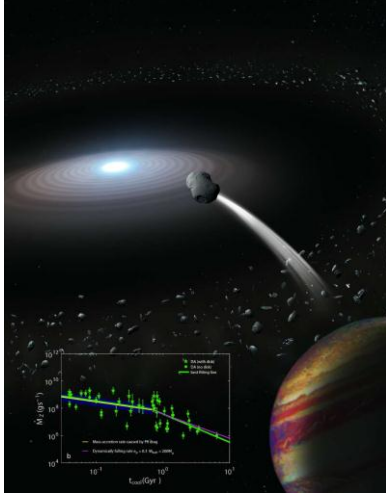


Figure 2: An evolution diagram for tidally disrupted asteroid model.

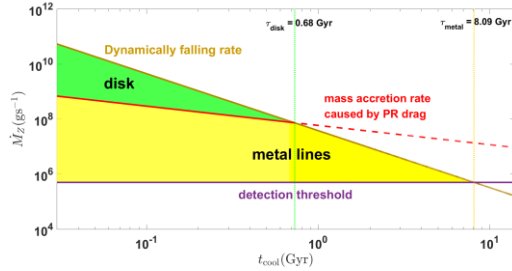


Figure 3: A power law decay evolution scenario for polluted white dwarfs. The brown line denotes the rate of mass falling into the Roche radius of the central white dwarf derived from the best fit of observational data. The mass accretion rate caused by the PR drag is plotted as the solid red line, together with its extrapolation to older cooling ages as a dash red line. The horizontal purple line represents the detection threshold. The intersections of these lines provide estimates of the timescales of disk lifetime (green area) and metal line detection (yellow area).

As shown in Figure 3, at the early stage, the rate of dynamically falling asteroids is larger than the maximum accretion rate driven by PR drag, thus dust can accumulate in the Roche limit and form an opaque disk continually supplying accretion at a rate of \dot{M}_{PR} . At the late stage, when the dynamically falling asteroids drops below \dot{M}_{PR} , there is not enough material supply, thus the disk begins dissipating and becomes optically thinner[7], which in turn reduces the accretion rate to keep balance with the income material. The transition time between these two stages therefore can be considered as the timescale of the disk phase, $\tau_{disk} = 0.68^{+0.25}_{-0.20}$.

Finally, the accretion rate will drop to a degree that metal lines in WD atmospheres become too weak to be detected. We obtain the critical timescale of detectable metal pollution, $\tau_{metal} = 8.09^{+2.16}_{-1.65}$.

In our scenario, the fraction of WDs with detectable disks to those with metal pollution is proportional to the fraction of their critical timescales. Therefore, the occurrence ratio of these two observational phenomena is predicted as:

$$f_{model} = \frac{\tau_{disk}}{\tau_{metal}} = 8.41^{+4.44}_{-3.66}$$

which is well consistent with the value derived from observations $f_{ob} = \frac{1\%-4\%}{25\%-50\%} = 2\% - 16\%$.

Conclusion The presence of disks is mainly at the early stage of the whole process of metal pollution, which is detectable until ~ 8 Gyr[8]. The success of this scenario also implies that the configuration of an asteroid belt with an outer gas giant might be common around stars of several solar masses.

References::

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