The Metal Polluted White Dwarfs and their Circumstellar Disks

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Abstract

Atmospheric metal features in the spectra of white dwarfs are regarded as anomalies, because any primordial metal in WDs would sink rapidly in short timescale as long as the stars are not hot enough. It is believed that this atmospheric pollution is mainly due to the accretion of the circumstellar matters, such as a debris disk inferred from their infrared excess in the spectra. To date, many samples of polluted WDs have been reported, and theories are put forward to explaining the detected results. This review summarises the developments both in theory and observation of this topic. A comparison of models and comments are also included as the last part of this article.

1 Introduction

White dwarfs are the evolution destinations for most small mass stars in our universe when they consume fusion fuel entirely and cool down. The typical structure of a white dwarf contains a core of carbon or oxygen and an atmosphere of hydrogen(DA), helium(DB) or mixed composition (DAB, DBA) depending on the specific evolution during the period of asymptotic giant branch (Veras, 2016). In these atmospheres, any original or already existing metals (in astrophysics, the term "metal" usually refer to any elements heavier than helium) could only survive when the white dwarfs are still hot enough to support them by "radiation levitation" (Barstow et al., 2014). When the temperature of stars continue to decrease, the strong gravities of the white dwarf will dominate the dynamics, and those metal components would sink into stars in a quite small timescale, leaving only hydrogen, helium or some dredged-up carbon behind (Fontaine and Michaud, 1979). This timescale is much shorter than the evolution(cooling) timescale for white dwarfs (Frewen and Hansen, 2014). so in principle, we would predict a considerably small fraction of white dwarfs in the observation that shows metal contamination in their atmospheres.

However, the observation reveals that the fraction of atmospheric metal-rich WDs is much larger than the expected. At least 25% WDs imply heavy elements in their surfaces (Mustill et al., 2018), which become a mystery in astronomy. Given the short sinking time of metals in white dwarfs, there must be some external sources providing materials to the stars during the evolution. The current "standard" model argues that the

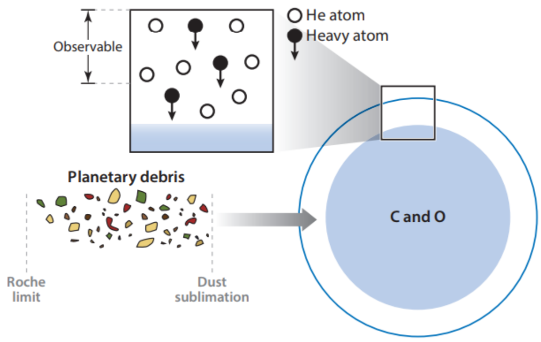

Figure 1: An illustration of an accreting DB white dwarf and gravitational sinking of heavy elements. Taken from Jura and Young (2014).

source is a dust/gas accretion disk within the Roche Radius of the white dwarfs, and its containment may come from a gravitational disruption of rocky asteroids during the post-main-sequence evolution (Farihi, 2016). It is believed that the Poynting-Robertson effect accounts for the accretion around white dwarfs (Xu and Jura, 2012), though some more detailed theories are needed for samples of extreme high accretion rate (Rafikov, 2011b). This "standard" model is corroborated by the data of detected disk from infrared spectra. Nevertheless, only a small proportion of metal polluted white dwarfs are observed with a detectable disk (Bonsor et al., 2017). Many discussions about the absence of detectable disk around those stars have been proposed (Jura, 2008; Farihi et al., 2010; Bochkarev and Rafikov, 2011). On the other hand, since the most in the field agree materials of the accretion disk come from one or several destruction events of asteroids within the Roche limit, the suggested mechanisms of delivering planetesimal into this small orbit vary (Debes et al., 2012; Petrovich and Muñoz, 2017; Bonsor and Wyatt, 2012), and still show limitation. To date, a completed and satisfying theory on metal polluted white dwarfs have not been developed yet, while many new samples of polluted white dwarfs are reported continuously (Farihi et al., 2017; Xu et al., 2018).

The remaining part of the article proceeds as follows: The Section 2 reviews the observation history of polluted white dwarfs, which is linked closely to the observation of circumstellar disks around white dwarfs. Next, Section 3 is concerned with the existing theories in this topic, including the properties, formation and accretion of the disk. Section 4 provides a discussion of these theoretical models, and a summary is given in Section 5.

2 Observation of pollution and circumstellar disks

The history of active observation of pollution phenomenon of white dwarfs is quite short and even shorter for their disks. Hubble Space Telescope and Spitzer Telescope played important roles in the observation and were accompanied by several large sky coverage projects, such as the Sloan Digital Sky Survey(SDSS), the Two Micron All Sky Survey(2MASS) and the Wide Field Infrared Explorer(WISE). Those projects provided dozens of (and growing) samples of polluted white dwarfs and valuable data about the detectable accretion disks in the last fifteen years. The observation of polluted white dwarfs consists of three parts: the metal features in spectra, inferred accretion rate, and the circumstellar disk.

2.1 Spectroscopic metals

The first discovery of photospheric metals feature in spectra is much earlier than the active research of this phenomenon. In 1917, Van Maanen reported the identification of "a very faint star of spectral type F" (van Maanen, 1919), which means that this star has strengthening spectral lines H & K of Ca II. It was found to be a white dwarf later on and named after its discoverer. Despite this pioneering work, the much more detailed analysis of spectrum was not available until the Hubble Space Telescope provided the high-resolution spectroscopy nearly 90 years later.

Up to now, a large number of white dwarfs with spectroscopic metals have been reported and revealed

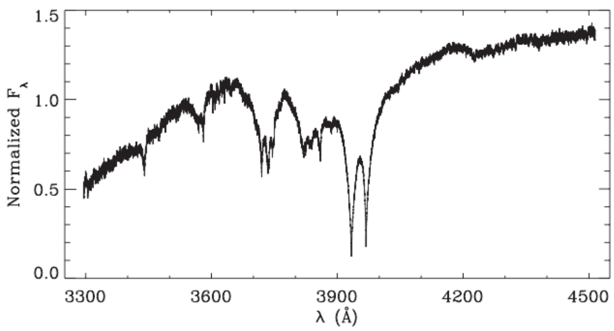

Figure 2: A spectrum in optical region of Van Maanen 2 using UVES on the VLT (Very Large Telescope). The feature of Ca, Mg, Fe could easily be seen. Taken from Farihi (2016).

variable and exciting signatures. Ca is the strongest feature of polluted white dwarfs, but by no means the only metal in their atmospheres (Veras, 2016). Figure 3 are the typical pieces of spectra of two polluted white dwarfs, and the metal composition detected has large variation (Gänsicke et al., 2012). The spotted include nearly all elements from Na(11) to Cu(29), while heavier elements like Sr(38) also appear in several samples (Veras, 2016). Those detected kinds of elements help us understand and determine the composition of inferred accreted materials, which may be from the remnant of planetary systems around those stars during the main-sequence period. The current observation indicates the bulk of accretion disk consists of earth-like rock elements(O, Mg, Si, Fe), as well as refractory lithophiles (Ca, Al, Ti) and siderophiles (Cr, Mn, S, Ni) (Jura and Young, 2014; Veras, 2016). It is worth mentioning that some white dwarfs show a high-enough proportion of oxygen in their atmospheres, which indicates that they are accreting materials consisted of water (Farihi et al., 2013; Raddi et al., 2015).

Not all white dwarfs observed with photospheric metals result from ongoing (or past) accretion, especially for those young and warmer white dwarfs, where radiation is high enough to play a role in dynamics. After considering the influence of radiation in their survey, which include DA white dwarfs with $17000K < T_{eff} < 27000K$, Koester et al. (2014) claimed that more than half (25 in 48) of metal-rich white dwarfs in their samples could be explained by radiation levitation alone. Most of them are at the warm end of the samples. For those left 23 polluted white dwarfs, the radiation levitation also reduces the inferred accretion rate required for achieving the observed metal abundance in their atmospheres (though accretion must be ongoing in those stars). A similar

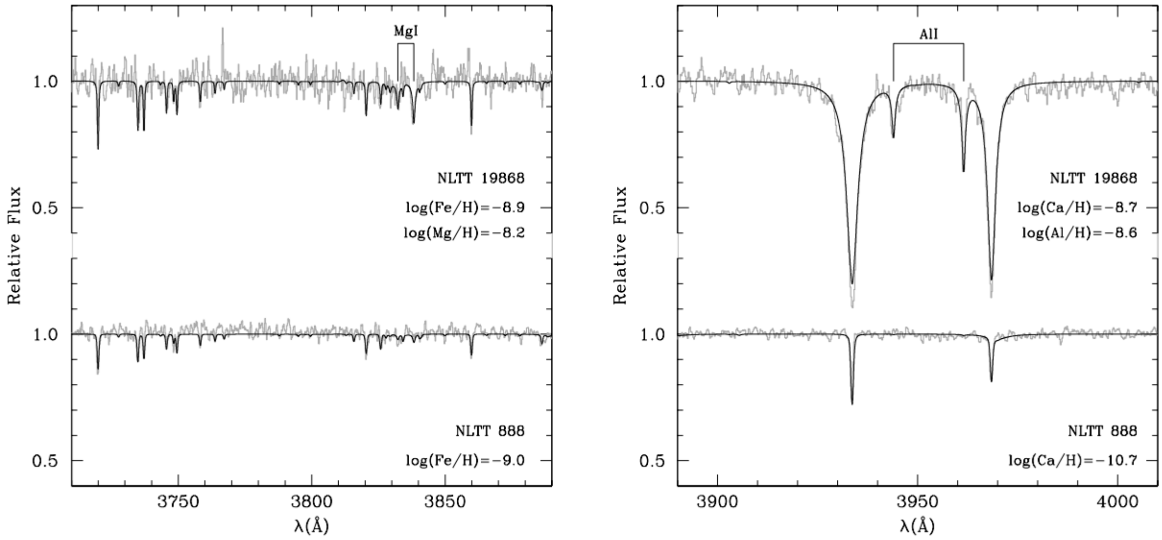

Figure 3: Typical pieces of spectrum (gray lines) of two polluted white dwarfs NLTT 19868 and NLTT 888 and the fitting spectra(black lines). While having similar elements, these two samples show notable differences in strength of lines. Taken from Kawka and Vennes (2016).

conclusion was given in Chayer (2014). Notice only hydrogen-rich white dwarfs are considered here, where the sinking timescale of heavy elements is much shorter. For helium-rich white dwarfs, the scenario of accretion could be different(see below).

2.2 Infrared accretion rate

Besides giving us insights into the chemical composition of accretion disks, the observation of spectroscopic metals also leads to the measurement of inferred accretion rate, a significant physical quantity in research of accretion disk. The inferred accretion rate (usually referred as $\dot{M}$) is defined as the mass of materials falling onto the star per unit second (in steady-state), and the magnitude of $\dot{M}$ provide a constraint of the structure and property of the accretion disk itself. It makes $\dot{M}$ useful in testing and selecting models of accretion of the white dwarfs (Kilic and Redfield, 2007). The term "inferred" here refer to the fact that the accretion rate is derived from the metal abundance in the atmospheres rather than being observed directly.

The accretion and photospheric metal abundance (deduced from the fitting of spectra with metal lines) are associated because of the confrontation between the accreting and gravitational settling. Given the particular white dwarfs parameters(cooling ages, main atmospheric composition, etc.), the sinking timescale of a specific element is fixed (and only have a small difference between elements, see Paquette et al. (1986)). The steady abundance of this element would only depend on the falling materials from accretion disk in this situation, and the steady state is reached when the accretion rate is equal to the mass loss due to diffusion happening at the bottom of the atmosphere, or more particularly, the convection zone. This relationship was first investigated by Dupuis et al. (1992, 1993a,b) and numerically it is represented as

$$X_i = \frac{\tau_i \dot{M}_i}{M_{CZ}} \tag{1}$$

In this expression, X is the mass fraction of a specific element i in the atmosphere; $\dot{M}_i$ and τ_i are the corresponding accretion rate and diffusion timescale of this element; M_{CZ} is the total mass of convection zone. It is noteworthy that the region we interest is where the chemical compositions are well-mixed, so considering those radiation dominated stars with a small convection zone, the M_{CZ} is generalized to become M_{CVZ} whose bottom depth is defined as the deeper of the bottom of CZ or Rosseland optical depth 5 (Koester, 2009).

It is straightforward to get the total accretion rate from the equation above:

$$\dot{M} = \sum \dot{M}_i = \sum \frac{X_i M_{CVZ}}{\tau_i} \tag{2}$$

this rate could also be written as:

$$\dot{M} = \frac{1}{A_i}\frac{X_i M_{CVZ}}{\tau_i} \tag{3}$$

where A_i is the mass fraction of element i in the accreted materials (Farihi, 2016). Ca, as the most remarkable signature in the spectra, are widely used as the choice in this estimator. The corresponding fraction A_{Ca} is approximately 0.016, from several detailed investigated samples where multiple elements are included in calculation (Zuckerman et al., 2010; Farihi et al., 2012b).

For DA stars with quite short diffusion timescales, we can safely conclude that the accretion rate we get from equation (3) is an ongoing and (in most time) steady one. However, for helium-rich white dwarfs, the accretion rate we derive may only reveal an average result rate over one or several diffusion timescales. It is a visible result given the typically longer time of gravitational settling of metals in those stars, which means those metals have a much larger probability to be observed even after the accretion have finished.

The inference above could be seen from another angle in the figure 4, plotting the inferred accretion rate as a function of the stellar temperature. The data set include all detected polluted white dwarfs with Spitzer from its first seven cycles (Bergfors et al., 2014). Some more metal-rich white dwarfs are detected in recent years but do not affect the main features. We can see clear trends that DBZ stars have higher accretion rate, and several DBZ stars showing high inferred accretion rates do not have infrared excess, which means their disks are not detected. This result may from the fact that the accretion has completed and metals remain in the atmosphere for several more diffusion timescales and are observed. This scenario cannot be achieved in DAZ stars where inferred accretion rate must refer to ongoing accretions, leading to a strong correlation between high rate and detected disk (Koester et al., 2014). It is notable that the time-averaged accretion rate of DBZ stars is larger than the ongoing rate for DAZ stars (Girven et al., 2012).

Though polluted white dwarfs distribute through the whole cooling evolution, we could only see few samples with high temperature (and young age) and low or modest inferred accretion rate. This may come from the observation bias for warm white dwarfs where radiation levitation is playing a role (Farihi, 2016), or the influence of temperature on ionization of tracing elements and atmospheric opacity (Koester and Wilken, 2006).

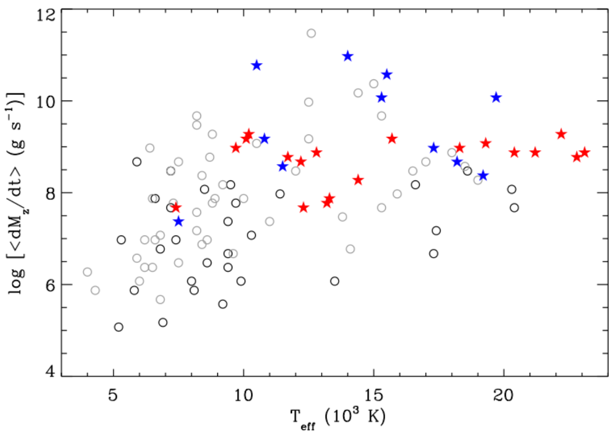

Figure 4: Accretion rate as the function of the stellar temperature of polluted samples identified by Spitzer IRAC. The inferred rates are deduced from known or estimated Ca abundance in the atmosphere. Hydrogen-rich(DAZ) stars with infrared excess are illustrated as red stars, otherwise as black circles. Helium-rich(DBZ) stars with infrared excess are plotted as blue stars, or grey circle otherwise. Taken from Bergfors et al. (2014).

2.3 Circumstellar disk

Searching for the signature from extrasolar planetary systems is another important topic in astronomy, and was not linked to the polluted phenomenon at the beginning. It turned out to be a quite challenging task in a bright infrared sky, and detecting circumstellar matters around the main-sequence stars also cost efforts in the history. Looking for them in the white dwarf systems is typically harder, given the brightness of circumstellar materials mainly depends on their host stars. The low luminosity of white dwarfs means much higher sensitivity is required to observe their circumstellar structures, and actually, only one dusty white dwarf with infrared excess was identified before 2005 (Becklin et al., 2005), before Spitzer telescope began to provide data (though the second sample came from ground observation, see citation above).

The first detected white dwarf with infrared excess is G29-38, which is confirmed by Zuckerman and Becklin (1987), using the NASA Infrared Telescope Facility. In their article, the excess was explained by an orbiting brown dwarf, which is unresolved and only seen from the spectrum. However, observation data in that following years do not support this hypothesis, and after several years of argument in literature (Wickramasinghe et al., 1988; Haas and Leinert, 1990; Graham et al., 1990), Keck Speckle Imaging (Kuchner et al., 1998) ruled out any companion around G29-38. At the same time, multiple kinds of metal were detected in the atmosphere of the star (Koester et al., 1997), making the interpretation of an accretion circumstellar disk widely accepted.

Since 2005, many samples with infrared excess have been reported from Spitzer and ground observa-

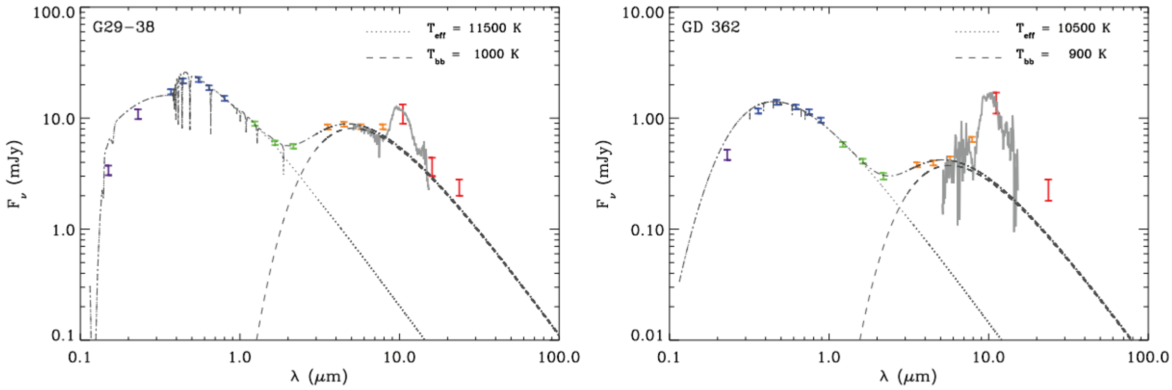

Figure 5: Infrared band Spectra of first two dusty and polluted white dwarfs G29-38 and GD 362. Colored error bars represent different photometric data: GALEX far- and near-ultraviolet (purple); optical UBVRI or ugriz (blue); near-infrared JHK (green); IRAC 3C8 m (orange); N-band, IRS 16 m, and MIPS 24 m (red). IRS 5C15 m spectra are also shown (solid grey). Stellar atmospheric models are plotted as dotted grey lines, and equal-temperature blackbody approximations to the disk emission are illustrated as dashed grey lines. Taken from Farihi (2016).

tions, and they only appear with polluted white dwarfs (Veras, 2016). Showing the properties of light absorption and re-emission, the infrared excess of them help us explore the main features of dust around white dwarfs. Several properties seem to share among those samples (Farihi, 2016): the corresponding circumstellar dust is commonly hot($1000K - 1500K$) and locate closely to stars, within the region of $0.7R_{\odot}$. They show strong silicate emission lines in spectra but reveal no emission from polycyclic aromatic hydrocarbons that appear in interstellar medium and comets. According to the spectra, the circumstellar matter around white dwarfs is deficient in carbon and terrestrially rocky (Jura, 2006; Jura et al., 2009).

Based on the observation, some theoretical works are proposed, and a fundamental model of the circumstellar disk around white dwarfs was built. It suggests that the dusty materials are in an opaque, geometry-flat disk, like Saturn's rings, and are completely within the Roche Radius of the host stars (Jura, 2003). The deduced radius comes from its relationship with disk temperature:

$$T \approx \frac{2}{3\pi}^{1/4}(\frac{R}{r})^{3/4}T_{eff} \tag{4}$$

where R and T_{eff} are the radius and effective temperature of the host star, and the expression of flux emitted from the disk given the temperature distribution (Jura, 2003):

$$F \approx 12\pi^{1/3}\cos(i_{LOS})\frac{R^2}{D^2}(\frac{2kT_{eff}}{3h\nu})^{8/3}\frac{h\nu^3}{c^2}\int_{x_{in}}^{x_{out}}\frac{x^{5/3}}{e^x-1}dx \tag{5}$$

Here D is the distance from the system to the earth, i_{LOS} is the inclination to the line of sight (it degenerates with the inner and outer radius of disk), and $x = h\nu/kT$. This model shows a good fit to the observation, see examples in Xu and Jura (2012). Though the similar fitting could realize by black-body radiation with proper temperature (Farihi et al., 2009), the optically thick and flat disk has a better physics meaning in its formation, which is consistent with the standard gravitational disruption model(see next section for the theoretical progress).

the basic model is not complete, and many modifications have been applied to explained different emission features, like halos and warped or flared disks involving optically thin region. They are constructed accounting for silicate emission (Jura et al., 2007; Reach et al., 2009).

Apart from the dust disk, gas in the circumstellar environment around those stars is also playing an essential role in evolution and accretion, especially for those without detected dusk disk (infrared excess). A gas-phase disk may exist in such systems (Jura, 2008), though gas emission is not detected yet without dust campion (Brinkworth et al., 2012). The gas components are identified by the double peak emission line, due to velocity-shift from rotations. For those detailed investigated samples, it is shown that gas and dust are spatially coincident (Melis et al., 2010), implying the physics link between the two components. The shapes of emission lines also show asymmetry sometimes and vary with time, indicating a high eccentric orbit and potential evolution in the systems (Melis et al., 2012;

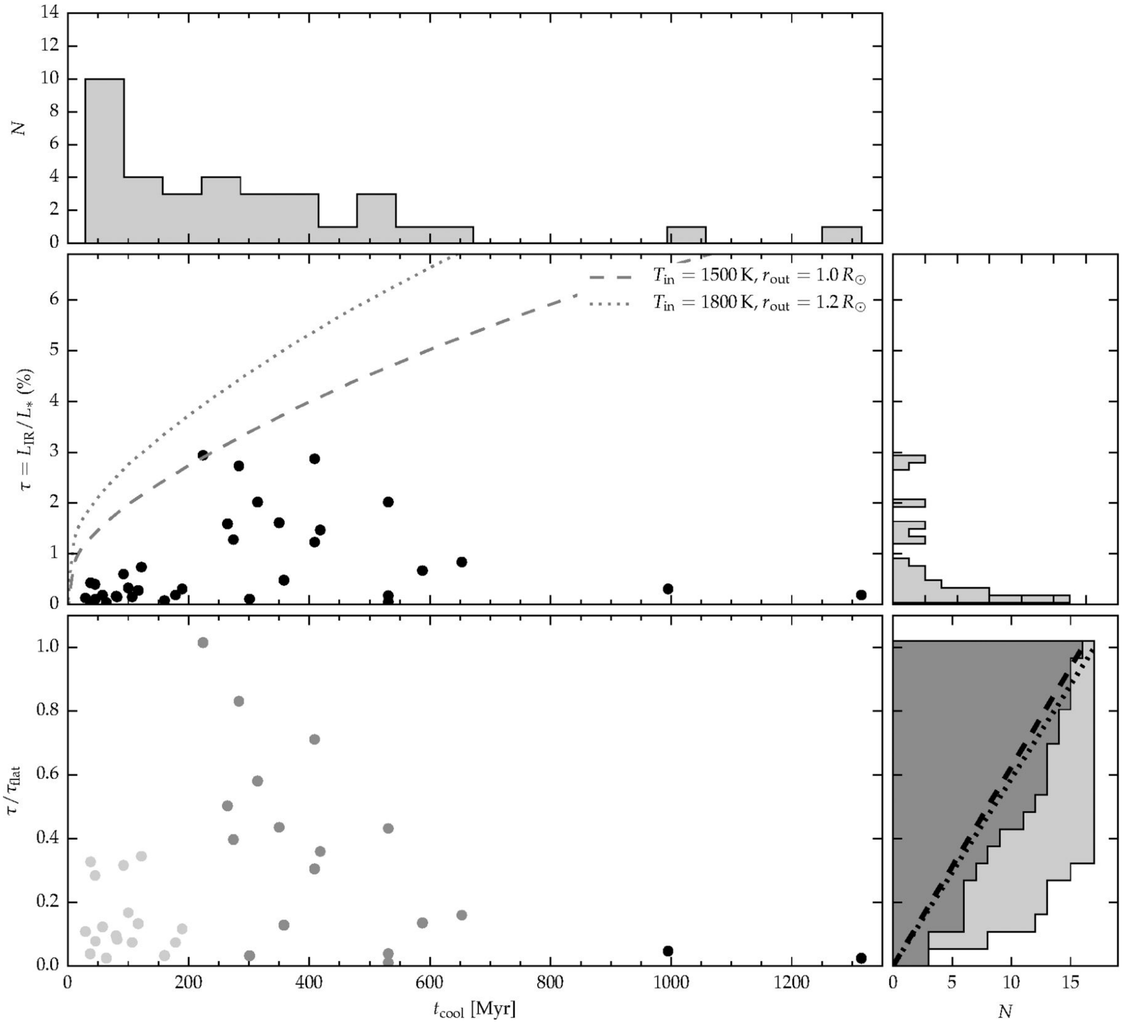

Figure 6: Fractional luminosity data of 35 detected disks over cooling ages. Upper panel: the histogram of disk numbers. More disks are found around young WDs. Center panel: The left figure shows the fractional luminosity $\tau = L_{IR}/L_*$ of disks as a function of ages, while the right histogram illustrates the distribution over the magnitude of τ. The theoretical prediction of a face-on($i = 0$), opaque flat disks with specfic parameters are given as dotted and dashed lines. Bottom panel: the ratio of observation and the theoretical value of τ. Different grey levels represent cooling age interval. The cumulative distributions of the ratio for light and dark grey target are shown on the right, and the dotted and dashed lines illustrate the theoretical distribution due to random inclination. Taken from Rocchetto et al. (2015).

Farihi et al., 2012a).

It is noteworthy that the maximum speed deduced from the double-peak shape of lines is on the order of $500km\ s^{-1}$, which is slower than excepted Keplerian value of $1000-3000km\ s^{-1}$ for an orbit within detected disk edge (Farihi, 2016). It might be a result of gas pressure and plays a role in Runaway model (Rafikov, 2011b). Some theoretical works have been done on modelling gas component of disk involving standard α accretion scenario (Hartmann et al., 2011, 2014) and are rather successful in reproducing the spectrum features.

Some other interesting observation results of disks are about their luminosity and distribution on stellar ages. Those data are represented in the figure 6. The upper panel shows the histogram of detected disk numbers over the cooling ages, and much more disks are observed around young and warmer white dwarfs. Despite the observation bias, the fraction luminosity of those disks is quite small, and relatively smaller than their counterparts around older and cooler stars, according to the center and bottom panel. This figure

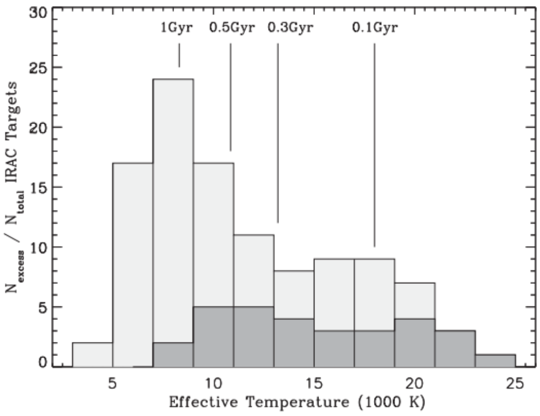

Figure 7: Histogram of the same samples of figure 4. The total detected polluted stars are represented by white rectangles, while the stars with infrared excess are illustrated by gray rectangles. Several typical cooling ages are labelled on the top of the figure. A clear trend could been seen that there are more polluted samples without detected disks as stellar ages growing up. Taken from Bergfors et al. (2014).

also provides a comparison of observation and theoretical value, and indicate the faintness of the detected disks is not a result of random inclination.

The sharp increase of disk number with the faintest fraction luminosity suggested that the majority of disks may escape from detection because they are below the sensitivity limit. That is why it is now believed that most polluted white dwarfs host accretion disks, though only a small proportion of them are identified with infrared excess (Rocchetto et al., 2015). The estimated fractional luminosity for polluted stars with the most modest accretion rate may be as low as 10^{-6} (Farihi et al., 2013), implying the same conjecture as above.

3 Theory of the polluted White Dwarfs

The theoretical research on polluted white dwarfs are associated with their (accretion) disks and had a substantial development in the past decade. While the asteroid disruption model remains the standard, the whole physics picture seems to be uncompleted yet. Many theories have been put forward explaining parts of data, but limitation still exists. This section is divided into three main topics: the adaptation of circumstellar materials, the mechanism of delivering asteroids, and the disk formation & accretion within Roche Radius.

3.1 Adaptation of circumstellar materials

Although now we associated the metal-rich phenomenon with circumstellar materials (accretion) naturally, this conclusion was not so apparent in the history. Until 1997, only one polluted sample did not fall into the category of cold, helium-rich white dwarfs (Koester et al., 1997). As we mentioned above, the helium-rich WDs have a much longer gravitational settling timescale for metal in their atmosphere, keeping showing metal feature in spectra for a long time even after accretion. Consequently, it was assumed that those heavy elements might come from the encounters with interstellar medium clouds and this idea appeared in the early literature (Dupuis et al., 1993a,b; Hansen and Liebert, 2003).

However, this hypothesis has two main problems. The first is the observed chemical composition of the atmosphere. If the helium-rich white dwarfs underwent an accretion of the interstellar medium, the huge amount of hydrogen they absorbed should leave features on spectra, which were absent in detected polluted stars (Aannestad et al., 1993). The Second problem is about the polluted hydrogen-rich stars, where the diffusion time scale can be as short as days. The photospheric metal in those stars means there much be ongoing accretion, leading to a strict constraint of the models for interstellar accretion. A detailed examined of ISM accretion model for DAZ stars (and a comparison with circumstellar accretion model) was given by Kilic and Redfield (2007).

Due to these two unsolved problems, people turned to consider accretion in circumstellar environments. A model of Oort-cloud like orbiting comets was put forward by Alcock et al. (1986), but soon met difficulties in explaining volatile-deficient property in accretion materials (Sion et al., 1990) and the distribution of elements abundance in samples (Zuckerman et al., 2003). On the other hand, more and more metal-rich (especially DA) white dwarfs with detected debris disks were discovered (Kilic et al., 2006; von Hippel et al., 2007) since the launch of Spitzer in 2003, and observation reveals the disk is terrestrially rocky(Jura et al., 2009). As a result, now the accretion debris disks made of rocky planetesimal are widely believed responsible for the photospheric metal in white dwarfs.

3.2 Mechanism of delivering asteroids

In section 2, we reviewed the basic model of a flat, opaque disk explaining the infrared excess of metal-

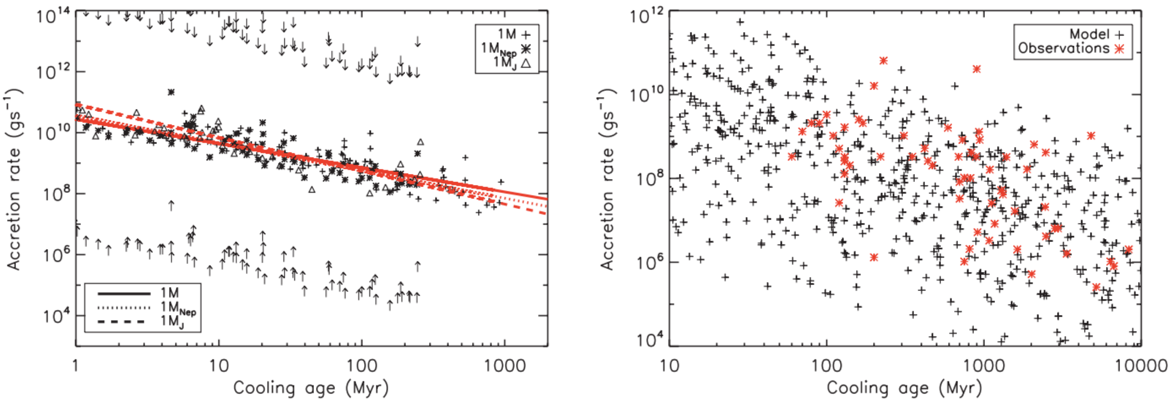

Figure 8: The simulation of accretion rates over cooling ages, based on a Neptune-Kuiper analogy model. The symbols in the left panel represent different mass of the poor planet: Cross and solid line for $M = 1M_{\oplus}$, asterisks and dotted line for $M = 1M_{Nep}$, Triangles and dashed line for $M = 1M_J$. A range of parameters are calculated according to Bonsor and Wyatt (2010), but only the median is illustrated. The upper and lower limits of $1M_{Nep}$ are given as arrows. The three lines are fittings of the medians. Those calculated accretion rates (using different system parameters) are plotted on the right panel as the black cross. As a comparison, the inferred accretion rate from observation are represented in the figure, as red asterisks. Taken from Bonsor et al. (2011).

rich white dwarfs in observation. This idea was first developed by Jura (2003), and in the same article, the asteroid disruption model was introduced. In this s-cenario, a parent asteroid orbiting very close to the white dwarfs is tidally destroyed by gravity, and form a disk that lies within the Roche limit. This scenario is corroborated by the observation, and events of asteroid disintegrating are reported in Vanderburg et al. (2015). It now has been the standard and basic mechanism in theory of the polluted white dwarfs (Bonsor et al., 2017).

The asteroid disruption model explains the physic-s after the planetesimal falls into the Roche limit, but mysteries remain in where those asteroids are from, and the physics to deliver them to the stars. Because of the mass loss during the asymptotic giant branch (AGB) of post-main-sequence evolution, the planetary systems which are stable during main-sequence may become unstable when star becomes a white dwarf (Mustill et al., 2014). This may result in a delivering of materials to stars, and several theoretical works have been done based on this idea and orbit resonances[1] (Bonsor et al., 2011; Debes et al., 2012; Veras et al., 2013; Petrovich and Muñoz, 2017).

[1]The orbit resonances are phenomena occur when two (or multiple) orbiting object having a periodic gravitational influence on each other, usually due to the integer ratio of their rotation period. The influence is cumulated for it always happens in the same or similar position, which may finally lead to instabilities and changes in orbits. See Wiki for more information.

In Bonsor et al. (2011), the asteroid (or comet) belt locates in an outer planetary system, an analog to Kuiper belt in the Solar System. A substantial mass in the belt could survive in the evolution to the white dwarfs, and the asteroids may scatter into the inner region of the system, or ejected outward and become unbounded. In the case of scattering in, those planetesimal are gravitational affected by a planet near the inner edge (just like Neptune for Kuiper belt) and rotate into the inner orbit, where an additional planet is presented and enlarge the eccentricity of asteroid-s' orbit. Finally, the periastron of the orbit fall into the Roche limit, and the objects are tidally destroyed there. This model successfully explains the inferred accretion we have, see figure 8. However, it is not a satisfying model, considering the spectroscopic observation shows that the accretion materials are deficient in volatile materials (Jura et al., 2009), which are rich in an outer Kuiper-like belt. Additionally, according to the observation of planetary systems around the main-sequence stars, the model predicts a higher fraction of polluted white dwarfs than observed (Bonsor et al., 2011). An Oort-like belt is also be discussed (Bonsor and Wyatt, 2012) but soon be found to be insignifican-t in mass contribution for observed metal abundance (Veras et al., 2014b).

Another possible belt position is within the terrestrial zone (especially, the region where materials could survive in post-main-sequence evolutions). Given the

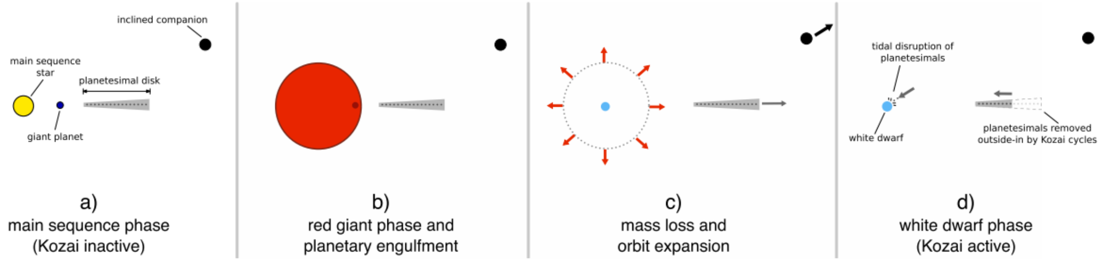

Figure 9: The physical picture for the planet engulfment model. Panel (a): the stable system during the main sequence. Panel (b): During the post-main-sequence evolution (mainly GB or AGB), the inner planet is engulfed by host star. Panel (c): the orbit of disk and campion expand because of mass loss of host star. Panel (d): the system is unstable now, and planetesimals are sent inward to be tidally destructed.

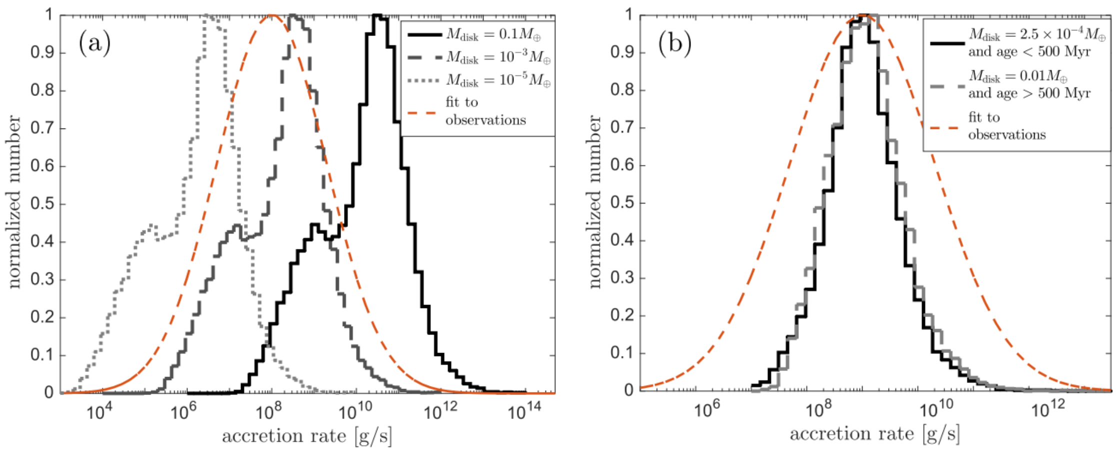

Figure 10: Calculated accretion rates using planet engulfment model. The results are given with assumption that all particle in disk have the same mass, and all materials delivered into Roche Radius are accreted into white dwarfs (which is not very physical, see text below) Left panel: the three predicted distribution of number over accretion rate with a disk mass of $1M_\oplus$ (solid line), $10^{-3}M_\oplus$ (dashed line), $10^{-5}M_\oplus$ (dotted line). The distribution of observation is plotted in red dashed line. Right panel: the samples in the left are divided into two age group (cooling ages $< 500Myr$ for black solid line and $> 500Myr$ for grey dashed line), and given proper mass of disk($2.4 \times 10^{-4}M_\oplus$ and $0.01M_\oplus$, respectively), they show good consistent with the observation. Figure 9 and 10 are both taken from Petrovich and Muñoz (2017).

accretion materials are detected to be rocky, this idea seems to be more plausible. It is fully discussed in several trigger mechanisms. In the original version of the terrestrial asteroid belt, the delivering are dominated by orbit resonance. A 2:1 interior resonance is shown to be sufficient to perturb the asteroids, sending them into the high eccentric orbits and disruptions (Debes et al., 2012). A similar calculation was given in Frewen and Hansen (2014). They are successful in explaining existing data, but the predicted mass of asteroid belt is much higher (about 10^2 to 10^4 times more massive) than the belt of solar system, which is not so realistic because the progenitors of those white dwarfs are typically A-type stars and only have 2-3 times more mass of the Sun. Though the observation does not rule out such high mass belt, it is hard for such massive belt to survive in evolution (Bonsor and Wyatt, 2010). A recent simulation includes a new trigger of planetary engulfment was represent in Petrovich and Muñoz (2017). The physics picture could be illustrated as in figure 9. A debris disk remains stable during the main sequence with an inner planet and an outer inclined companion star; During the post-main-sequence evolution, this planet is merged by the star, leading to an instability of the disk and finally the delivering of asteroids into the white dwarf. The planetary engulfment model provides a possible solution to the two problems above: The disk mass it requires is smaller than the former work (see figure 10), and it predicts a wider disk in radial, allowing a smaller surface density. That means it could survive more time during its collisional evolution (Petrovich and Muñoz, 2017).

It is worth to mention that about a half of mass will be scattered and become unbound during disruption (Rees, 1988), which influences the estimated mass of parent asteroid belts. The main problem of this model is the companion star required for dynamics is absent in most polluted samples we observed. The future completed observation may help us evaluate this proposal correctly. Another recent-proposed delivering mechanism including planet-planet scattering in post-main-sequence evolution is given in Mustill et al. (2018).

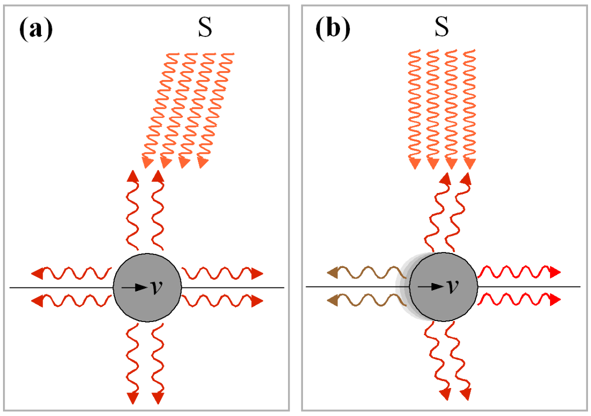

Figure 11: A rough explanation of Poynting-Robertson drag. A particle is rotating a radiation source(S). (a)In the reference frame of the particle, the radiation comes in slightly ahead due to light aberration. The corresponding radiation pressure slows down the particle, making it orbits inward. (b)In the reference of the source(S), the re-emission of absorbed radiation is not isotropic due to the motion of the particle. More momentum is taken by photon emitted forward, slowing down the particle itself. In both frames, the result is that the particle is "dragged" towards the radiation source (usually stars). Figure taken from Wiki: Poynting-Robertson effect.

3.3 Within the Roche Radius

Regardless of the mechanism of delivering, the objects sent into the Roche Radius face a similar destiny: be torn apart by the gravity of white dwarfs. Typically, the perturbed asteroids follow a high eccentric orbit ($e > 0.98$) with a semi-major axis of several AUs and the destruction events happen at the periastron. The fragment of planetesimal would have the similar trajectory as before and form a collisionless, eccentric ring of debris (Veras et al., 2014a). It is assumed that the radiation effect (more particularly, the Poynting-Robertson drag) dominate the dynamics in the following evolution, convert the high eccentric orbit into a nearly-circular one. The related calculations are presented in Veras et al. (2015).

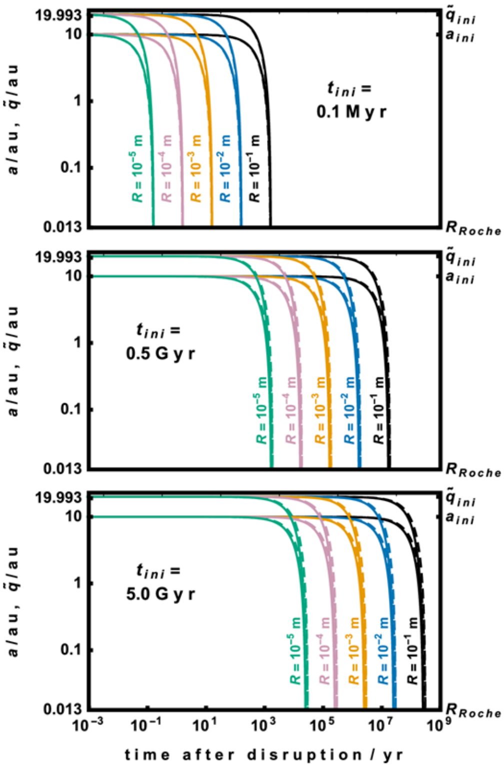

Figure 12: Estimated shrinking disks for different particle sizes and cooling ages with corresponding luminosities $22L_\odot$, $2 \times 10^{-3}L_\odot$, $1 \times 10^{-4}L_\odot$. a is the semi-major axis (lower lines) and $q = a(1+e)$ is the apocentre (upper lines). The eccentricity becomes zero when two lines meet. The solid and dashed lines represent numerical integration and analytical approximation respectively in the source article. It is clear from the figure large fragments require much more time to be pulled into Roche Radius. Taken from Veras et al. (2015).

Though this idea gives the basic framework of the disk evolution, it is not completed considering the observation. The timescale for dragging large fragments into Roche Radius is quite long (see figure 12), and the eccentric ring feature should be notable in the observation at least for a fraction of polluted samples. However, we did not detect such shrinking disk out of Roche limit yet, indicating some other mechanism

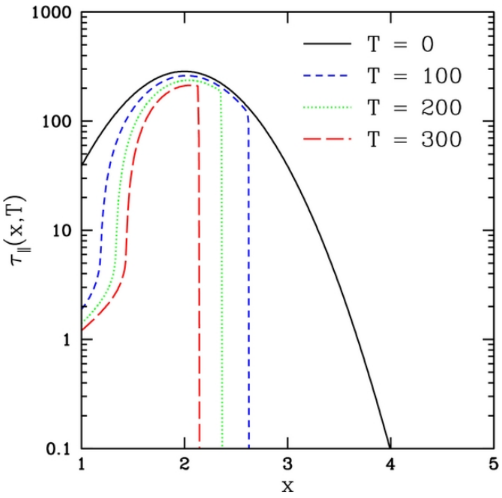

Figure 13: The evolution of opacity depth as a distribution over radius, where $X = r/R_{in}$ represent the times of inner disk edge. Distributions of the disk are given on several specific time step. The original disk distribution follows a approximate gaussian with $x_0 = 2, \sigma = 0.7$. During the evolution, a sharp outer edge and an optically thin region at the inner edge are produced. Taken from Bochkarev and Rafikov (2011).

is involved for the quick contract of rings. The collision and sublimation are believed to play roles in this period (Farihi, 2016): The smaller fragments in the disk are pulled into Roche Radius quickly, where the disruption occurs. It leaves a proto-disk full of small dust and gas. Due to the high Keplerian velocity near the host star, the violent collisions of succeeding larger fragments in this region make them break into small pieces, which could be dragged by P-R force more efficiently. Additionally, the proto-disk is exposed to the radiation of the white dwarfs, leading to sublimation and the generation of gas. These gas (along with those produced in collisions) may provide viscosity to slow down the speed of large fragments, help them fall into the Roche Radius. The similar gas-generating scenario is discussed in Jura (2008).

As mentioned earlier, the basic model of the materials within the Roche Radius is an opaque, geometric-flat debris disk. The disk remains flat because any vertical momentum will be cancelled out by collisions between particles. During the disk evolution, the stellar radiation makes a sharp outer edge of the disk and an optical thin inner region where P-R effect is efficient to transport mass (Bochkarev and Rafikov, 2011). Its illustration is given in figure 13. The gas component is believed to coexist with the dust spatially, with a pressure-induced hight of roughly 1/100 white dwarf radius (Metzger et al., 2012). The gas should also appear within the sublimation-sufficient radius, and constitute the major component of materials accreted into the white dwarfs (Rafikov, 2011b).

The final part of the theory section is about the accretion model. The current theoretical work believes the P-R effect is the primary mechanism here and it is quite successful in explaining most samples with low or modest accretion rates we have (Rafikov, 2011a). However, some polluted white dwarfs are inferring extremely high accretion rate, and all of them are helium-rich stars (see figure 4). Some models are proposed dealing with the observation, and the most developed one is called the Runaway accretion, from Rafikov (2011b), followed by an extended article from Metzger et al. (2012). In this model, the accretion is first dominated by P-R drag, and a sufficient mass of dust is sublimated at the inner age of the debris disk. Then the bulk of gas move inward to pollute the host star, and its angular momentum is transferred to the rest gas, making it spread outward. Because of the gas pressure, the gas is rotating slower than its dust counterpart, causing an angular momentum transfer between them. It accelerates the inward transport of dust, which in turn produces more gas as positive feedback. If the coupling between dust and gas is strong, the resulting accretion rate could be high enough to explain the detected samples. An illustration of the model is given in figure 14.

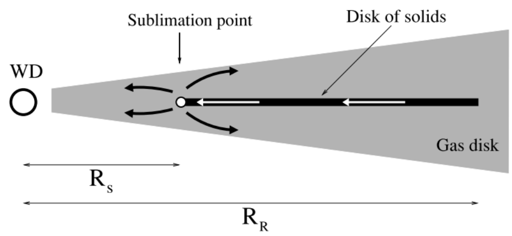

Figure 14: An illustration of Runaway model. Gas disk is plotted in grey and dust in black. R_s is the sublimation-sufficient radius, where gas is generated. The following fluxes of gas are represented by black arrows. White arrows show the migration of dust materials. R_R is the Roche Radius, as usual. Taken from Rafikov (2011b).

This model interprets the spatial coincidence of gas and dust thorough the evolution naturally, and the absent of gas emission feature in some samples may just because not enough dust has been sublimated yet. A discussion on disk chemistry and a detailed treatment of ionization of this model are presented in Feng and Desch (2017). Despite being a plausible scenario, this model also has some shortcomings. The positive

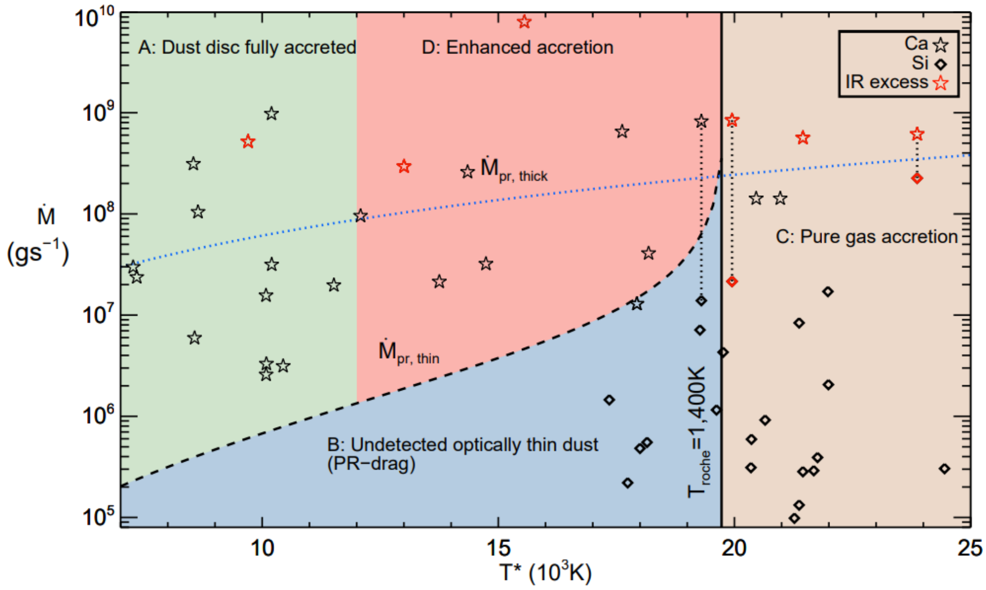

Figure 15: The illustration of different disk scenarios. The inferred accretion rate is given in a function of stellar temperature. The whole space is divided into four regions: (A)a finished accretion, (B)optically thin disk, (C)entirely gas disk, (D)enhanced accretion from optically thin or gaseous scenario to explain the accretion rates. The stars and diamonds represent pollution-observed samples whose accretion rate are inferred from Ca and Si respectively. Stars with infrared excess are plotted in red. The black dashed line is the calculated accretion rate from an optically thin disk and blue dotted line is its counterpart for an optically thick disk. Taken from Bonsor et al. (2017).

feedback indicated an exponential increase of accretion rate and rapid exhaustion of debris disk, and predict a smaller proportion of high accretion rate stars than the observed (Metzger et al., 2012), even considering the long diffusion timescale of DB stars. Also, it meets difficulties in explaining those samples with both high rate and detected disks, for the disk disappears quickly after the high inferred rate is reached. A possible solution is that disk exhaustion and a new disruption event occur in a single diffusion timescale, allowing the photospheric metal from the former and disk from the latter could be detected simultaneously.

A disk of gas may also reproduce the extreme sample we have because it can easily provide the high-enough rate by the standard α accretion (King et al., 2007). This possibility is discussed in Jura (2008); Bear and Soker (2013). Different from the Runaway model, the outburst usually happens at the early stage of disks when a substantial mass of gas is generated. It usually leaves a dust disk evolving via P-R effect. They are more likely to responsible for high accretion rate samples with disks.

As a special interest of human beings, the detection of water in exo-planetary systems always attract wide attention. After two polluted white dwarfs implying water accretion are reported (Farihi et al., 2013; Raddi et al., 2015), a thorough theoretical research work of water in post-main-sequence evolution are present by Malamud and Perets (2016, 2017a,b,c) in a series of papers. The survival of potential sources of water (ice) and the relative scarcity in detections are discussed, in a range of mass parameters of minor planets and host stars. The water appeared in white dwarfs provide clues in the search for habitability in those planetary systems, in return, the water retention may help distinguish if the pollution is from multiple small accretions, or single massive accretion (Malamud and Perets, 2017c).

4 Discussion

The Last section presents a rough picture of polluted white dwarfs from accretions. Though a substantial development have been seen in the past decade, many things remain unknown, mainly due to the limitation from observation. As we mentioned above, Based on the infrared excess and emission feature in the spectra, the detected polluted samples show significant variations, from the chemical composition of accretion materials, planetary environments, to the morphology of the disks. Some models have been proposed for the variances, include warped or flared disks (Jura et al., 2007; Reach et al., 2009). The trend of variations is continuing with new samples being reported (Farihi et al., 2017; Xu et al., 2018). These variances may come from differences in initial conditions, but also indicate transient phases and evolution in those systems. At least a few samples are identified with variation patterns during years observation (Manser et al., 2016; Farihi et al., 2018), showing quick transformations in small timescales. Unfortunately (or fortunately), the theoretical work to date is far from complete, and many more efforts are required to understand the variations.

Another challenge from observation is the absence of detected disks for the majority of polluted white dwarfs. From figure 6, it is believed that most of the disks escape from being observed because they are fainter than the sensitivity limit. Theoretical discussions of disk structure responsible for this phenomenon was seen in many former papers (Jura, 2008; Farihi et al., 2010; Bochkarev and Rafikov, 2011), and is summarized by the review from Bonsor et al. (2017): depending on the property of the system and inferred accretion rate, the absence of disks may be explained by (i)an entirely gaseous disk, (ii)an opaque but narrow disk, (iii)an optically thin disk, (iv)a finished accretion process and the disk is exhausted already. (iv) is only valid for those oldest polluted white dwarfs. These four situations can explain different samples, given certain cooling ages and inferred accretion rates. An illustration is presented in figure 15. The opaque but narrow disk could cover the whole region in the figure, as long as the disk is compact and slim enough (Bonsor et al., 2017). The pure gas accretion happens when the temperature at Roche Limit exceed the sublimation one, evaporated the materials completely within the radius. Gas may also come from the collisions, or in the early stage of disk formation (Jura, 2008; Bear and Soker, 2013), but condensation should be considered fully in those scenarios (Metzger et al., 2012).

Lastly, Veras et al. (2017) discussed a new disruption mechanism for asteroids in a conference. This mechanism includes the YORP (Yarkovsky-O'Keefe-Radviesvki-Paddock) effect, which could accelerate the spin angular velocity of asymmetric asteroids around radiation sources(stars). The centrifugal force will finally break the asteroids into debris, and then they may be scattered by planets and orbit into host stars, contributing the pollution.

5 Summary

This article presents and reviews the major progress of research on polluted white dwarfs in the past years, including theories and observations. In general, we have learned a lot about these metal-rich stars. The pollution comes from rocky asteroids, which is tidally disrupted within the Roche Radius of host stars. The asteroids may come from terrestrial-zone or outer region analogous to the Kuiper belt, and show chemical composition similar to the bulk of the earth. We also constructed the model of the accretion disk, which is mainly based on an opaque, geometric-flat disk. This assumption is consistent with samples, and some modifications could be adopted for explaining at leat a part of variances in observations.

On the other hand, many things remain in the dark currently. The mechanism of delivering planetesimal into Roche Radius is not clear, though many models have been proposed. Those models usually suggest additional planets as remnants of planetary systems or companion stars, but we can not accept or rule out those assumptions simply because they are not found yet. It poses a challenge to distinguishing the proper one in those theories. Also, some theoretical efforts have been made in explaining the variations of disks and accretions, including those variations in detected disks and possible models for undetected ones, but a completed theory has not been established yet. More details of those planetary systems and disks structure identified in the future observations may shed light on those problems.

Despite the complex task of understanding pollution in white dwarfs, the rewards are also valuable. The photospheric metal of white dwarfs provides a unique insight into the composition and structure of remnant of planetary systems during the post main sequence (Jura and Young, 2014; Bonsor and Xu, 2017). It could not be done in the main-sequence system because of the effect of strong radiation.

Many sky survey projects involving infrared or far-infrared observation are ongoing nowadays, like those with ALMA and JWST. The galaxy survey mission of GAIA may also identify the predicted giant planets around those metal-rich stars. With more detailed and thoroughly examined data, the complete understanding of polluted white dwarfs could be expected in the future.

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