PLANETARY SYSTEMS AND REAL PLANETARY NEBULAE
FROM PLANET DESTRUCTION NEAR WHITE DWARFS

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ABSTRACT

We suggest that tidal destruction of Earth-like and icy planets near a white dwarf (WD) might lead to the formation of one or more low-mass – Earth-like and lighter – planets in tight orbits around the WD. The formation of the new WD planetary system starts with a tidal break-up of the parent planet to planetesimals near the tidal radius of about $1R_\odot$. Internal stress forces keep the planetesimal from further tidal break-up when their radius is less than about 100 km. We speculate that the planetesimals then bind together to form new sub-Earth \textit{daughter-planets} at a few solar radii around the WD. More massive planets that contain hydrogen supply the WD with fresh nuclear fuel to reincarnate its stellar-giant phase. Some of the hydrogen will be inflated in a large envelope. The envelope blows a wind to form a nebula that is later (after the entire envelope is lost) ionized by the hot WD. We term this glowing ionized nebula that originated from a planet a \textit{real planetary nebula} (RPN). This preliminary study of daughter-planets from a planet (DPP) and the RPN scenarios are of speculative nature. More detail studies must follow to establish whether the suggested scenarios can indeed take place.

1. INTRODUCTION

The first white dwarf (WD) where IR excess has been observed G29–38 \textsuperscript{[Zuckerman & Becklin, 1987]} was spectroscopically observed also to contain unexpected metals in its atmosphere (e.g., \textsuperscript{Reach et al, 2009}). Today more than 35 circumstellar dusty disks around WDs are known (e.g., \textsuperscript{von Hippel et al, 2007; Brinkworth et al, 2009; Farihi et al, 2010a, b, 2012; Dufour et al, 2010; Melis et al, 2010, 2011; Girven et al, 2012; Kilic et al, 2012; Xu & Jura, 2012; Bergfors et al, 2014; Rocchetto et al, 2015}). The composition of these WDs, as deduced from spectra, is consistent with accretion from asteroids or comets, but not with accretion from the ISM (e.g., \textsuperscript{Sion et al, 1990; Zuckerman et al, 2003; Jura, 2003; Jura et al, 2006; Kilic & Redfield, 2007}).

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Gänzicke et al. 2007, 2008; Farihi et al. 2010a). IR excess from WDs (e.g. Becklin et al. 2005; Kilic et al. 2005, 2006; Jura et al. 2007a,b, 2009a; Mullally et al. 2007; Kilic & Redfield 2007; Jura 2008; Farihi et al. 2009, 2010a,b, 2011a; Farihi 2011b; Girven et al. 2012; Brinkworth et al. 2012) is commonly attributed to dusty disks formed from tidal destruction of small bodies near the WDs (e.g., Zuckerman & Becklin 1987; Graham et al. 1990; Brinkworth et al. 2009; Jura et al. 2009a; Farihi et al. 2010a,b, 2011a; Debes et al. 2012; Veras et al. 2014a).

The orbits of planets and the sub-planet bodies, hereafter planetary system objects (PSO), are mainly stable throughout the stellar evolution, after their formation and after dynamical settling (Tsiganis et al. 2005; Levison et al. 2011). However, planetary migration, close encounters and binary companions can act to destabilise systems at latter times. Furthermore, a stellar binary companion can form extremely eccentric planetary orbits through the Kozai mechanism (Davies et al. 2014). It is though that after the massive envelope ejection by stars on the asymptotic giant branch (AGB), some orbits become unstable during the post-AGB phase and beyond, even in systems that were stable up to this late evolutionary time (Debes & Sigurdsson 2002; Nordhaus et al. 2010; Bonsor et al. 2011; Veras et al. 2011, 2013; Vovatizs et al. 2013; Frewen & Hansen 2014; Mustill et al. 2014; Veras & Gänzicke 2013). For example, the orbits of surviving planets increase due to the mass-loss in a manner that might lead to instabilities of the orbits of PSO (e.g., Veras et al. 2014a; Mustill et al. 2014). These PSO might later be tidally disrupted and collide with the WD remnant of the AGB star (e.g., Soker et al. 2010; Veras et al. 2014a; Di Stefano et al. 2015). Due to the variety of composition and orbital parameters other scenarios are possible as well. For example, Veras et al. (2014a) investigate the tidal disruption of highly eccentric asteroids as they approach WD and establishes that spherical asteroids break up and form highly collisionless rings. Debes et al. (2012) show that mass-loss from the star during the post-main-sequence stage can cause resonances between planetesimals and a giant planet.

The relevant PSO can be classified into three groups as follows.

1. Small bodies of a progenitor planetary system like asteroids, comets and small moons. When tidally destructed these lead to the WD pollution as discussed above (e.g., Bergfors et al. 2014; Farihi et al. 2014; Wilson et al. 2014 and references therein).

2. Earth-like and icy planets can be destructed to planetesimals. Some planetesimals will be directly accreted to the WD. In section 2 we study the tidal destruction to planetesimals and propose that some surviving planetesimals might form sub-Earth planets. We term this process daughter-planets from a planet (DPP) since the new planetary system that is formed is composed of the tidally destroyed planet.

3. Gas giant planets that contain sufficient hydrogen mass of \( M_{H,p} \gtrsim 10^{-3} M_\odot \), set a nuclear burning on the WD. In section 3 we argue that the end product might be an expanding nebula around a hot WD. This we term a real planetary nebula (RPN), as the nebular gas
comes from a planet.

While previous studies investigated in detail PSOs in the first group, here we concentrate on PSOs in the second and third groups. We do not model these scenarios in detail, but rather provide a series of arguments to speculate on the final outcomes of the tidal disruption of bodies larger than asteroids, i.e., planets. In sections 2 and 3 we discuss two possible, somewhat speculative, outcomes from the tidally destructed planet. The initial evolution of unstable orbits is common to the two cases, but the final outcome is determined by the composition and size of the initial planet. Icy planets, or Earth-like planets which are tidally destructed will lead to DPP and Gas giant planets will lead to RPN. We summarize these points in section 4.

2. PLANETESIMAL FORMATION

2.1. Tidal destruction

Although tidal destruction of planets near WDs has been discussed before (see Sec. 1), we turn to evaluate the size of surviving planetesimals, something that was omitted from previous studies. We study the process of tidal destruction when an Earth-like planet or an ice giant reaches the tidal radius around a WD. Gas giant planets that contain hydrogen are discussed in section 3. The tidal destruction ceases when internal solid forces are about equal to tidal forces. Planetesimals are formed from the solid part of the planet. In ice giant planets the icy envelope is of lower density and will be tidally stripped before the solid core is destructed.

We consider below the final destruction of the parent planet. In reality the planet can be destructed during a number of periastron passages. For example, Guillochon et al. (2011) found planets of \( \gtrsim 0.25M_J \) to survive the first passage in their assumed orbit, although it already lose mass at that first passage. Since we study the latest evolution of the material of the destructed planet, our proposed scenarios work also for planet destruction in several passages.

The tidal radius for a metal core is given by

\[
R_t \simeq C R_* \left( \frac{\rho_*}{\rho_p} \right)^{1/3} \simeq 0.65 \left( \frac{C}{1.26} \right) \left( \frac{M_*}{0.5M_\odot} \right)^{1/3} \left( \frac{\rho_p}{5 \text{ g cm}^{-3}} \right)^{-1/3} R_\odot, \tag{1}
\]

where \( R_* \) and \( M_* \) are the radius and mass of the WD, respectively, \( \rho_* \) is the average density of the WD, and \( \rho_p \) is the density of the planet’s metal core. \( C \) is a constant that depends on the assumption used in deriving the expression (for more details see Harris 1996).
states the range of values for $C$ to be $1.26 - 2.9$, depending on the properties of
the destructed object. The tidal radius $R_t$ (which ranges from $0.65 - 1.5R_\odot$) meaning is that
when the center of the planet reaches this distance to the center of the WD, tidal forces start
breaking-up the planet.

Equation (1) holds as long as there are no other forces beside gravity. However, when the
shredded pieces of the core decrease, at a certain size, internal forces can hold them against
gravity, similar to the way mountains exist on Earth. The maximum size is determined
by the equality of the stress resulting from gravity to an internal property of the material
called tensile strength. It is usually expressed as ultimate tensile strength (UTS), $\sigma_s$ (e.g.,
Boehnhardt 2004 and reference within). UTS is the maximum stress a material can withstand
(before breaking apart) while being pulled.

In our setting, the maximum ‘weight’ the UTS can hold is $W_s = \sigma_s A$, where $A \approx R_{pl}^2$
is the cross section area of the planetesimal. The ‘weight’ due to the differential gravity of
the WD is $W_d \approx \rho_{pl} g_d R_{pl}^3$, where $\rho_{pl}$ is the density of the planetesimal and the differential
gravitational acceleration exerted by the WD at the tidal radius is

$$g_d = \frac{2GM_\ast R_{pl}}{R_t^3}. \quad (2)$$

Taking $W_s \gtrsim W_d$ we derive the condition on the radius of a spherical planetesimal that is
held by the UTS

$$R_{pl} \lesssim \frac{\sigma_s}{\rho_{pl} g_d}. \quad (3)$$

For a future use we define from this equation the maximum differential acceleration that the
UTS can withstand

$$g_\sigma \equiv \frac{\sigma_s}{\rho_{pl} R_{pl}}. \quad (4)$$

We note that fractures can occur not only at the UTS limit due to tension but also at
the limit of the compressive strength due to crushing. The compressive strength is usually
higher than the tensile strength but for elastic composition can cause distortion and fractions
in the material. The tensile strength for rocks found in San Marcos, for example, range from
$125 - 580\text{ M Pa}$, depending on the composition (Huirong-Anita & Thomas 2004). Meteorites
which are considered as a rubble pile material have lower tensile strengths that range from
$2 - 62\text{ M Pa}$ (compressive strength can range between $20 - 450\text{ M Pa}$; for more details
see Popova et al. 2011). Our core composition is unknown. We scale the UTS with $\sigma_s = 100\text{ M Pa}$ and the planetesimal density to be similar to that of the Earth core (Pepe et al.
2013).

Substituting equation (2) into equation (3) we derive the maximum planetesimal size
that can be held by the UTS as a function of the tidal radius.
\[
R_{pl} \approx \left( \frac{\sigma_s}{\rho_{pl} 2GM_s} \right)^{0.5} \approx 100 \left( \frac{M_s}{0.5M_\odot} \right)^{-\frac{1}{2}} \left( \frac{\rho_{pl}}{5 \text{ g s}^{-1}} \right)^{-\frac{1}{2}} \times \left( \frac{1 \times 10^9 \text{ dyn cm}^{-2}}{\sigma_s} \right)^{\frac{1}{2}} \left( \frac{R_t}{0.65R_\odot} \right)^{\frac{3}{2}} \text{ km.} \quad (5)
\]

The simple calculation leading to equation (5) does not take into account the self gravity of the planetesimal. To do so we introduce to the equation the acceleration due to the gravity of the planetesimal:

\[
g_{pl} = \frac{4\pi G\rho_{pl} R_{pl}^3}{3 R_{pl}^2}. \quad (6)
\]

The condition to hold the planetesimal against tidal break-up reads

\[
g_d < g_{pl} + g_\sigma. \quad (7)
\]

Substituting equations (2), (4) and (6) into equation (7), gives

\[
\frac{2GM_s}{R_t^3} < \frac{4\pi}{3} G\rho_{pl} + \frac{\sigma_s}{\rho_{pl} R_{pl}^2}. \quad (8)
\]

Setting \(\sigma_s = 0\) yields equation 1. Equation (8) sets an upper limit on the size of the solid bodies, planetesimal to Earth-like planets, to survive. In figure 1 we plot this limit (solid blue line) on the planetesimal/planet size (radius) as a function of its distance from the WD center.

As can be seen from figure 1 the planetesimals survivability is a function of their radius and their orbital separation from the WD. Dashed arrows depict the evolution route discussed here for icy or Earth-like planets. First, solid planet, or the solid core of an icy planet, is tidally destructed when it approaches the WD (black vertical arrow) and crosses the tidal radius at \(R_t = 0.65R_\odot\) in the setting used here. Planetesimals are formed around \(R_t\) with decreasing size as tidal forces continue to act. Eventually, below the planetesimal radius given by equation (8) and drawn in solid-blue line, UTS holds the planetesimal intact. Some planetesimals fall-in and accreted by the WD (red arrows). From the surviving planetesimals (green arrows), we propose here, a new sub-Earth planet might be formed.

\[2.2. \text{ Evaporation}\]

Let us discuss a specific system that might shed light on our proposed scenario and its limitations. Silvotti et al. (2014) claimed for the presence of three Earth-like planets
Fig. 1.— The orbital distance ($r$) vs. the planetesimal radius ($R_{pl}$). The figure represents the formation scenario of a DPP. The blue line depicts the tidal destruction radius of solid bodies with a density of $\rho_{pl} = 5 \text{ g cm}^{-5}$ near a WD of mass $M_* = 0.5 M_\odot$ as given by equation (8). Large bodies are held by their gravity, while small bodies by internal forces. In the region above the blue line the bodies are stable, while below the line they are destructed by the tidal force of the WD. The dashed lines present the evolution studied here. The vertical black-dashed line represents an Earth-like planet approaching the WD, until its distance is below the tidal destruction radius and it breaks-up to planetesimals. Some planetesimals are accreted (red lines), while some survive (green lines) and, we speculate here, merge to form lower mass sub-Earth planets. Some of the the surviving planetesimals are spread to larger distance of up to several solar radii. This is not drawn here.
orbiting the sdB star KIC 10001893. The respective orbital periods of the planets they have found are $P_1 = 5.273$ hours, $P_2 = 7.807$ hours, and $P_3 = 19.48$ hours. This star is an extreme horizontal branch (EHB) star that burns helium in its core and contains a very little envelope mass (Baran et al. 2011; Østensen et al. 2011). Spectroscopically, EHB stars are classified as hot subdwarf (sdB or sdO) stars. In order to become an sdB star, the red giant branch (RGB) stellar progenitor must lose most of its envelope. These stars retain a hydrogen envelope of less than about $0.001 \, M_\odot$ (Baran et al. 2011). The small orbital separations of the planets from the sdB imply that the system went through a common envelope (CE) phase, or that the planets are second generation planets formed in a post-CE phase with a star (e.g., Perets 2010; Tutukov & Fedorova 2012). Silvotti et al. (2014) assumes a standard sdB mass of $M_{\text{sdB}} = 0.47 \, M_\odot$, $\log g \approx 5.35$, $T_{\text{sdB}} = 27500$ K and $R_{\text{sdB}} \approx 0.24 \, R_\odot$. Therefore, the estimated luminosity of KIC 10001893 is $L_{\text{sdB}} \approx 30 \, L_\odot$.

Stellar binary companions (e.g., Han et al. 2002, 2007) and planets (Soker 1998) can perturb the envelope of RGB stars, mainly via a CE evolution, and lead to the ejection of most of the envelope (for a single star scenario see, e.g., Yi 2008). The envelope ejection leads to the formation of an EHB star. If the claimed planets around KIC 10001893 are real, then there are two possible scenarios for the system formation. (1) A stellar companion spiraled-in to the core, and was destroyed. The spun-up envelope formed a disk where the planets formed. These are second-generation planets (e.g., Beer et al. 2004; Perets 2010; Tutukov & Fedorova 2012). (2) One or more planets entered the envelope of the RGB progenitor and removed its envelope to form the EHB star (Soker 1998). Only the last planet survived after the entire envelope has been removed (e.g., Bear & Soker 2011b). It was an icy planet or lighter. The Earth-like planets were formed from the tidal destruction of this last planet (Bear et al. 2011). This second possibility is according to the dynamical scenario proposed here. However, there is one limitation that prevents our proposed scenario to occur around very hot stars.

Since these planets orbit an sdB star whose luminosity is higher than that of an old WD, their evaporation should be rapid. More significant, the planetesimals that are formed from the tidally destructed original planet are evaporated on a much shorter time scale than planets do. Below we present a simple calculation that shows that planetesimals will be evaporated in less than a year, shorter than the expected time for planetesimals to form a planet. We hereby relay on two estimations of evaporation time scales by Stone et al. (2015) for comets and by Owen & Wu (2013) and Bear & Soker (2011a) for planets:

Stone et al. (2015) in their equation 11 estimate the timescale of a comet (that is com-
posed of ice or rock) to completely sublimate as

\[ t_{ev} = \frac{16\pi R_c Q_{C,V} \rho_c r^2}{3 L_{WD}} \approx 0.01 \left( \frac{R_{pl}}{100 \text{ km}} \right) \left( \frac{Q_{C,V}}{3 \times 10^{10} \text{ erg g}^{-1}} \right) \left( \frac{r}{1R_{\odot}} \right)^2 \left( \frac{L_{sdB}}{30L_{\odot}} \right)^{-1} \text{ yr}, \] (9)

where \( R_c \) is the comet radius and \( \rho_c \) is the comet density which in our case are equal to \( R_{pl} \) and \( \rho_{pl} \) respectively, \( Q_{C,V} \) is the latent heat of transformation (similar for both ice and silicates), \( r \) is the orbital distance and \( L_{WD} \) is the luminosity of the WD, which for KIC 10001893 is the luminosity of the sdB star. According to equation (9) based on Stone et al. (2015), the planetesimals will be completely sublimated within several days.

We note that the Yarkovsky-O’Keefe-Radzievski-Paddock (YORP) mechanism, that spins-up an asteroid to a break-up rotation velocity, works on a much longer time scale for the planetesimals discussed here. Scaling the results of Veras et al. (2014b) to the sdB star discussed above for \( r = 1R_{\odot} \) and \( R_{pl} = 100 \) km, we find the break up to occur at a time scale of > 100 yr. This is much longer than the evaporation time of these bodies. Indeed, the YORP effect is usually discussed with regards to small bodies with a size of 10 km or less (Veras et al. 2014b).

Owen & Wu (2013) describe the evaporation rate of a planet caused by high energy photons (EUV and X-rays) near solar type stars as

\[ \dot{M} = \frac{\eta L_{HE}}{4G\rho r^2} \sim 10^{17} \left( \frac{L_{sdB}}{30L_{\odot}} \right) \left( \frac{r}{R_{\odot}} \right)^{-2} \left( \frac{\eta R}{10^{-2}} \right) \text{ g s}^{-1}, \] (10)

where, \( L_{HE} \) is the luminosity in EUV and X-ray. We defined \( \eta_R \equiv \eta_{HE} \), where \( \eta_{HE} = L_{He}/L_{sdB} \) is the fraction of stellar radiation that is emitted in the EUV and X-ray, and \( \eta \) is the efficiency of the process discussed by Owen & Wu (2013). Scaling \( \eta \) based on figure 12 of Owen & Wu (2013), we have \( \eta = 0.05 - 0.2 \). Since in our case we have an sdB star, we evaluate the number of energetic photons (\( \lambda \leq 912\text{Å} \)) from the entire spectrum as \( \eta = 0.15 \). Therefore, \( \eta_R \approx 0.01 \). For this case a 100 km planetesimal will evaporate within less than 0.01 yr. We support this approximation (Eq. 10) with the different evaporation rates presented in Bear & Soker (2011a). Bear & Soker (2011a) calculate that at \( 1R_{\odot} \) from a 0.5\( M_{\odot} \) sdB star the sublimation rate exceeds \( 10^{14} \text{ g s}^{-1} \) (depending on the model considered). This lower limit of evaporation rate will completely evaporate planetesimals of 100 km in a timescale of a year.

To summarize, Stone et al. (2015) took into account the evaporation rate of comets near a WD, Owen & Wu (2013) calculated the evaporation rate of planets near solar type stars and Bear & Soker (2011a) calculated the evaporation rate from a planet including recombination near an sdB star. All of these models suggest that the planetesimals formed at \( 1R_{\odot} \) near an sdB star will completely evaporate within a year.
The assembling process of a planet from planetesimals is complicated and the time scale depends on the size of the planetesimals, properties of the central star, the orbital distance and other parameters. Kenyon & Bromley (2014) calculated this timescale for different solar masses ($0.1M_\odot$, $0.3M_\odot$ and $0.5M_\odot$) and evaluate the timescale for planetesimals of the order of 100 km to become an embryo of 1000 km to be $\tau_{\text{pl,em}} \sim 5 \times 10^5 - 10^7$ yr at 2.5 AU depending on the initial mass of the disk and the stellar mass. The Keplerian timescales for the cases studied by Kenyon & Bromley (2014) are

$$t_{\text{orbit}} \approx 6 \left( \frac{R}{2.5 \text{ AU}} \right)^{\frac{3}{2}} \left( \frac{M_*}{0.5M_\odot} \right)^{-\frac{1}{2}} \text{yr},$$ (11)

We define the ratio

$$\zeta \equiv \frac{\tau_{\text{pl,em}}}{t_{\text{orbit}}} \approx 10^5 - 10^6. \quad (12)$$

The Keplerian timescale for the newly formed planetesimals in KIC 10001893 studied by Silvotti et al. (2014) is $t_{\text{orbit}} \approx 5 \times 10^{-4}$ yr. Taking $\zeta$ to be as in the equation (12) we estimate the timescale of embryo formation to be $\tau_{\text{pl,em}} \approx 50 - 500$ yr. According to our evaporation estimate the planetesimals will be completely evaporated within less than a year and hence no embryo can form.

We conclude that in the case of KIC 10001893 evaporation prevents planetesimals to form sub-Earth planets. Furthermore, the planets existence is debatable according to the evaporation rate (Stone et al. 2015). We note that a magnetic field might shield Jupiter-like planets from extensive evaporation (Bear & Soker 2012). Silvotti et al. (2014) suggested such magnetic fields inhibiting evaporation of the planets around KIC 10001893. It is not clear thought whether Earth-like planets will posses a strong enough magnetic field to slowdown evaporation. For planetesimals we do not expect that magnetic field will prevent evaporation.

3. REAL PLANETARY NEBULA (RPN) FORMATION

A real planetary nebula (RPN) is defined by us as an ionized nebula formed by mass lost from a giant star that was rejuvenated by a planet. Namely, the nebular gas was once part of a planet. We here propose, echoing Corradi et al. (2015), that the collision or a tidal destruction of a gas giant planet with a WD can lead to a RPN. Plausible progenitor systems to the RPN are post-common envelope binaries (PCEBs) with planetary systems around them. Properties of such systems are summarized by Zorotovic & Schreiber (2013) and Schleicher & Dreizler (2014). Schleicher & Dreizler (2014) studied 12 PCEBs, elaborating...
on NN Ser. A recent summary of the question on whether the planets are first-generation planets, i.e., were formed with the stellar binary system, or second generation planets (e.g., Völschow et al. 2014), i.e., formed in the post-CE phase from a circumbinary disk, is given by Bear & Soker (2014) and Schleicher et al. (2015). We note that PCEBs are only one possible formation route to RPNs.

It is important to note that there is a question as to the real presence of planets in some of these systems. In particular, some systems, if real, seem to be dynamically unstable, e.g., HW vir, QS vir, and NSVS1425, (e.g., Horner et al. 2012, 2013; Wittenmyer et al. 2013; Hinse et al. 2014) and in a recent paper Hardy et al. (2015) disprove the existence of a brown dwarf companion in V471 Tau. We here assume that such systems exist, and that instabilities can send some planets into the central binary system. The collision of planets with WDs should not be considered too speculative as we already mentioned in previous sections.

Collision of a planet with a hot core of an AGB (or post-AGB) star was discussed before (Harpaz & Soker 1994; Siess & Livio 1999; De Marco & Soker 2002). There are differences between these studies and the RPN scenario. (1) In the above listed studies the contribution of the planet to the ejected mass was lower than half. The largest contribution of the planet mass is in the calculations of Harpaz & Soker (1994), where for four cases a planet of mass \(0.01M_\odot\) was destroyed inside an AGB envelope of mass \(0.02M_\odot\). (2) The planet in these studied were destroyed near a hot core that still has a hydrogen burning in a shell. The injection of more hydrogen can change the burning properties, but the burning already exists. In the RPN scenario the hydrogen from the planet sets a new burning phase on the WD. Namely, in the RPN scenario the gas from the planet is fully responsible for the reformation of an AGB-like star. The relevant process from these studies is that the accretion on to the WD is via an accretion disk. This can lead to the launching of jets, and to extra mixing of the outer layers of the core.

When a planet of mass \(M_p \approx 1 - 10M_J\), where \(M_J\) is the mass of Jupiter, approaches a WD, or an sdB star, it is tidally destroyed at radius \(R_t\) as given by equation (11). First the hydrogen-rich envelope of the planet is removed, and then its metallic core. As discussed in Section 2 the metallic core is actually fragmented to many planetesimals. However, no planet will be formed as the hydrogen starts to burn on the WD. The high temperature evaporates the planetesimals.

About half of the gas from the destructed planet might escape the system, but about half of the gas stays bound and forms an accretion disk. The accreted hydrogen gas starts to burn on the surface of the WD. The accretion time scale can be up to hundreds time the dynamical time scale at the tidally destruction radius, i.e., several weeks. This leads to an
accretion rate of $\dot{M}_{\text{acc-t}} \gtrsim 0.01M_\odot \text{ yr}^{-1}$. A WD cannot accommodate such a rate, and a red giant envelope is inflated (Nomoto et al. 2007). A post AGB star with a core mass of $\approx 0.6M_\odot$ maintain a giant envelope ($R \gtrsim 100R_\odot$) as long as the envelope mass is $\gtrsim 10^{-3}M_\odot$ (Soker 1992). Around a cold WD of $\approx 0.6M_\odot$ even a lower mass of $\sim 10^{-4}M_\odot$ is sufficient to inflate a giant envelope (Hachisu et al. 1999). More massive WD require less mass to inflate an envelope (Hachisu et al. 1999).

In cases where there is a PCEB that causes the planet-WD collision, there is now a binary system inside the rejuvenated AGB star. Namely, a CE structure. The nebular mass is much smaller than any of the two stars. This situation resembles in some respects nova ejection that covers its binary system progenitor. To learn about the outcome we turn to examine nebulae formed by novae.

Many nova ejecta posses bipolar (or elliptical) shapes (e.g., Woudt et al. 2009; Chesneau et al. 2011, 2012; Shore et al. 2013). The expansion velocity of novae is typically high, $v_e \gtrsim 500 \text{ km s}^{-1}$ as the hydrogen or helium burn in a thermonuclear run-away, and the mass is very low, much below $0.001M_\odot$. However, in some cases slower components are observed (e.g., Chesneau et al. 2011). In the systems we study here the accreted hydrogen is not degenerate and the mass is much larger. Hence, expansion velocities will be much lower.

It is thought that the CE during the nova ejection shapes the bipolar nebula with possible mass concentration in the equatorial plane (e.g., Livio et al. 1990; Paresce et al. 1995). It is quite possible, therefore, that the bipolar structures of RPNe might result from a CE structure formed during a planet destruction. The major differences between novae and RPNe are (i) the ejection speed in novae are much higher, and (ii) the ejecta mass in novae is much lower. But the basic formation of bipolar nebulae might be similar.

The possibility of an RPN was already discussed by Corradi et al. (2015) as one possible explanation for the three PNs Abell 46, Abell 63, and Ou5. These have post-CE close binary systems, and very low nebular mass. The mass in each of these nebulae is much lower than the AGB envelope mass required to bring a wide binary system to a close orbit. Hence, Corradi et al. (2015) raised the possibility that the CE phase of these binary systems took place a long time ago, and the present low-mass nebula is a remnant of a planet. The general structure of these three PNe is bipolar with an equatorial ring.

In principle the RPN scenario does not require a close binary system. But it does require some instability in a planetary system to cause a planet collision with the WD. A Kozai-Lidov mechanism induced by a far-away binary companion is another possibility to cause a planet to collide with a WD. In the present study we do not consider the dynamical evolution that leads to planet-WD collision, and that is the same for the DPP and RPN
scenarios.

4. SUMMARY

We conducted a study of planets that are tidally destructed by WDs. Although rare, these types of transient events are expected to be found with future surveys, and be able to teach us about planetary systems around evolved stars.

The destruction of asteroids was studied in detail in the past. In this paper we speculated on the consequences of tidal destruction of planets. We did not model these scenarios in detail. We rather suggested plausible scenarios to the final outcomes of tidal disruption of bodies larger than asteroids. Earth-like planets and cores of icy planets which are tidally destructed might lead to the formation of daughter-planets from a planet, the DPP scenario. The newly formed daughter-planets are low-mass planets (Earth-like planet or less). Gas giant planets that are tidally destructed might cause the formation of real planetary nebulae (RPNe). Although the outcomes are different and are the direct result of the composition and mass of the planet (i.e., the hydrogen amount) both outcomes result from the same dynamical evolution leading to a tidal destruction of a planet.

When an Earth-like planet or an ice giant reaches the tidal radius around a WD, the metal core is tidally destructed and ≈100 km planetesimals are formed. The planetesimals survivability is a function of their radius and their orbital separation from the WD. Some planetesimals will be accreted by the WD but some that survive might merge to form one to few new sub-Earth planets. For ice giant planets the icy envelope is of lower density and will be tidally stripped before the solid core is destructed. The solid core then evolves as an Earth-like planet and might lead to the formation of a planetary system.

Gas giant planets contain hydrogen that complicates and enriches the outcome. Part of the hydrogen that is accreted onto the WD starts to burn. The now hot WD evaporates any surviving planetesimals from the tidal-destruction process. The tidal destruction process and the friction inside the accretion disk that is formed can supply hydrogen at a rate much higher than what the WD can accommodate. Part of the hydrogen then inflates a giant envelope. This rejuvenates giant star loses part of the envelope in a wind that forms a nebula. Later the central object shrinks, heats up and ionizes the nebula, like in a planetary nebula. We term this nebula whose material comes from a planet, a real planetary nebula (RPN). This scenario was mentioned by Corradi et al. (2015) in their study of some very low-mass PNe.

The collision or tidal destruction of a planet near stars beyond the main sequence can occur not only around cool WDs, but around hot sdB stars as well. In this case the
planetesimals will be evaporated due to the high luminosity of the hot sdB star and a planet is unlikely to form.

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