METAL ACCRETION ONTO WHITE DWARFS CAUSED BY POYNTING–ROBERTSON DRAG ON THEIR DEBRIS DISKS

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ABSTRACT

Recent discoveries of compact (sizes \( \lesssim R_\odot \)) debris disks around more than a dozen metal-rich white dwarfs (WDs) suggest that pollution of these stars with metals may be caused by accretion of high-Z material from the disk. But the mechanism responsible for efficient transfer of mass from a particulate disk to the WD atmosphere has not yet been identified. Here we demonstrate that radiation of the WD can effectively drive accretion of matter through the disk toward the sublimation radius (located at several tens of WD radii), where particles evaporate, feeding a disk of metal gas accreting onto the WD. We show that, contrary to some previous claims, Poynting–Robertson (PR) drag on the debris disk is effective at providing metal accretion rate \( M_{\text{PR}} \approx 10^3 \) g s\(^{-1}\) and higher, scaling quadratically with WD effective temperature. We compare our results with observations and show that, as expected, no WD hosting a particulate debris disk shows evidence of metal accretion rate below that produced by the PR drag. Existence of WDs accreting metals at rates significantly higher than \( M_{\text{PR}} \) suggests that another mechanism in addition to the PR drag drives accretion of high-Z elements in these systems.

Key words: accretion, accretion disks – protoplanetary disks – white dwarfs

Online-only material: color figure

1. INTRODUCTION

Recent infrared observations with Spitzer and ground-based facilities (Zuckerman & Becklin 1987; Graham et al. 1990; Farihi et al. 2010) revealed near-infrared excesses around more than a dozen metal-rich white dwarfs (WDs). This emission was interpreted as reprocessing of the WD radiation by refractory material residing in an extended, optically thick and geometrically thin disk (Jura 2003; Jura et al. 2007), similar to the rings of Saturn (Cuzzi et al. 2010).

It was hypothesized by Jura (2003) that such compact disks of high-Z material may be naturally produced by tidal disruption of asteroid-like bodies entering the Roche radius of the WD. This idea naturally explains the well-defined outer radii \( R_2 \) by \( \sim M_*/\rho \) of disks since the Roche radius \( R_R \) for tidal disruption of a self-gravitating object of normal density (\( \rho \approx 1 \) g cm\(^{-3}\)) by \( M_*/M_\odot \) central mass is \( R_R \approx (M_*/\rho)^{1/2} \approx 1 R_\odot \) (Jura 2003).

Moreover, Jura (2003) went on to suggest that the high-Z material contained in compact disks is responsible for the observed metal enrichment of a significant fraction of WDs. Accretion of this circumstellar material at high enough rate \( M_Z \) onto WD could maintain a non-zero abundance of metals in the WD atmosphere against rapid gravitational settling. This scenario thus provides a promising alternative to the previously widely discussed interstellar accretion model of WD metal pollution (Dupuis et al. 1993), which is known to have serious problems.

Observed abundances of heavy elements in WD atmospheres and theoretical calculations of their gravitational settling imply typical metal accretion rates \( M_Z \approx 10^5–10^6 \) g s\(^{-1}\) (Farihi et al. 2009, 2010). An evolving disk of debris must be able to supply such high \( M_Z \) to the WD. However, the question of how high-Z elements get transported to the WD atmosphere from the ring of solid particles, which does not extend all the way to the WD surface, has not yet been answered.

In principle, a dense ring of particles should evolve simply because of the angular momentum transfer due to inter-particle collisions, in full analogy with the rings of Saturn. However, the evolution timescale of Saturn’s rings due to this process is too long, \( \sim 10^9 \) yr (Salmon et al. 2010), and resultant values of \( M_Z \) are negligible.

Another natural mechanism driving debris toward the WD is due to stellar radiation interacting with the disk and giving rise to the Poynting–Robertson (PR) drag (Burns et al. 1979). Previously, Farihi et al. (2010) claimed that PR drag cannot provide \( M_Z \) higher than \( 10^3–10^4 \) g s\(^{-1}\) and dismissed this process as irrelevant. The goal of this paper is to critically re-examine the effect of radiative forces on the debris disk evolution and to show in particular that the PR drag can give rise to \( M_Z \) inferred from observations.

2. MASS ACCRETION DUE TO RADIATIVE FORCES

We envisage the following conceptual picture of the circum-WD environment. A dense disk (or ring) of particles lies inside the Roche radius \( R_R \) of the WD and evolves under the action of external agents, e.g., radiation forces. Particles migrate through the disk toward the sublimation radius \( R_s \), where their equilibrium temperature equals the sublimation temperature \( T_s \):

\[
R_s = \frac{R_s}{2} \left( \frac{T_s}{T_i} \right)^2 \approx 22 R_\odot T_{s4}^2 \left( \frac{1500 \text{K}}{T_i} \right)^2, \tag{1}
\]

where \( R_s \) is the WD radius, \( T_s \approx 1500 \) K for silicate grains, and \( T_{s4} \equiv T_s/10^4 \) K is the normalized stellar temperature \( T_i \). Taking \( R_s \approx 0.01 R_\odot \) typical for massive (\( M_\odot \geq 0.6 \) M\(_\odot \)) WDs (Ehrenreich et al. 2011), one finds \( R_s \approx 0.2 R_\odot \), in agreement with observationally inferred inner radii of compact debris disks (Jura et al. 2007, 2009a). Thus, for cool WDs \( R_{\text{out}}/R_{\text{in}} \) is several.

Particles sublimate at \( R_s \) feeding a disk of metallic gas, which we assume to be transparent to stellar radiation (gaseous component has been detected in several WDs with debris disks,}
solids (black) near the sublimation point at ± are the bulk density and characteristic size of the constituent

\[ \dot{M}_{\Sigma} = \alpha \frac{L_\ast \phi_r}{4 \pi r^2 c} \psi, \]  (5)

where \( c \) is the speed of light and \( \psi \) is the factor that characterizes the phase lag of radiative momentum deposition in disk particles and is specified later in Sections 2.1 and 2.2 for PR drag and Yarkovsky force, respectively. Factor \( \phi_r \) characterizes the efficiency of radiative momentum absorption by the disk surface. In the geometrical optics limits (particle size \( a \) much larger than characteristic wave length of stellar radiation)

\[ \phi_r \approx 1 - e^{-\tau}, \quad \tau_1 \equiv a^{-1} \tau, \]  (6)

where \( \tau_1 \) is the optical depth encountered by incident photons as they traverse the full disk thickness. Optically thick debris disks have \( \phi_r = 1 \).

Azimuthal force causes radial drift of disk material at speed \( v_r = 2 f_v / (\Omega K \Sigma_d) \), where \( K \) is the Keplerian angular frequency. This gives rise to mass transport at the rate

\[ \dot{M}_Z(r) = 2 \pi r v_r \Sigma_d = a \psi \frac{L_\ast \phi_r}{\Omega K r c}. \]  (7)

Note that for radiative forces both \( f_v \) and \( \dot{M}_Z \) are independent of \( \Sigma_d \).

It is reasonable to neglect the effect of potentially non-zero WD magnetic field on the evolution of particulate disk. However, simple estimate (Elsner & Lamb 1977) shows that for \( \dot{M}_Z \approx 10^8 \, \text{g} \, \text{s}^{-1} \) magnetic field stronger than 1 kG at the WD surface would suffice to disrupt the gaseous disk at \( R_s \). For simplicity, we assume here that the WD has weaker field and disregard complications related to magnetic effects.

### 2.1. Poynting–Robertson Drag

In the case of PR drag factor \( \psi \) is (Burns et al. 1979)

\[ \psi_{PR} = \frac{\Omega K r}{c} \approx 3.3 \times 10^{-3} \left( \frac{M_{\ast, J}}{0.2 \, R_\odot} \right)^{1/2} \]  (8)

leading to

\[ \dot{M}_{PR}(r) = 4 \phi_r \frac{R_s \, L_\ast}{3 \pi c^2} \approx 10^8 \, \text{g} \, \text{s}^{-1} \phi_r \frac{L_\ast}{10^{-3} L_\odot} \frac{20}{r/R_\odot}, \]  (9)

where we used Equations (4) and (7).

The numerical estimate in Equation (9) does not agree with the calculation of Farihi et al. (2010) and we demonstrate the origin of this discrepancy by following these authors and considering the inner edge of the disk where particles sublimate...
behind them. Dividing the mass of a disk, from which mass is transported onto the WD atmosphere, by the width of the annulus is $\tau_a = \frac{\rho a R_{\star}^{2} \Omega_{\star}}{c}$, which follows from the relationship $\tau_a/l \sim \tau_{\parallel, a}/l$ (here $h \ll R_{\star}$ is the disk thickness, $\tau_a$ and $\tau_{\parallel, a}$ are the vertical and horizontal optical depths of the annulus). Particles inside this annulus experience stronger PR drag and migrate toward the WD faster than particles outside the annulus. The transition occurs at the width of the annulus is $h/(\alpha \phi_r)$, which follows from the relationship $l_{PR} \sim \tau_a R_{\star}/l_{PR}$, where $\alpha$ and $\phi_r$ are the ratio of particle size to object's spin period and $\tau_a$ is the surface temperature of the WD, respectively.

Previously, Graham et al. (1990) obtained an empirical estimate of $M_{PR}$ by assuming accretion to be driven by PR drag and dividing the observationally inferred disk mass (surface area exposed to starlight (i.e., $r_{\parallel, a} \sim 1$) with radial optical depth of the annulus). Particles inside the annulus are shadowed by other particles nearby (thermal emission of debris disk may consist of 10–100 cm particles. If $R_{\star}$ is center of the disk directly illuminated by anisotropic starlight. This is because the latter illuminates the disk at small angle $\alpha$ and most of the particle surface is shadowed by other particles nearby (thermal emission of stars).
these particles is on average isotropic in horizontal direction). From heuristic arguments, one then expects stellar heating to be mainly deposited at small colatitude $\sim a^{1/2} \ll 1$ from the particle spin axis. It is easier for thermal conduction to isotropize surface temperature distribution around the spin axis over this small polar cap region rather than over the whole particle surface (as is assumed in standard calculation of $\psi_Y$), and this additionally lowers $\psi_Y$.

Thus, even if material properties of disk particles are favorable for maximizing $\psi_Y$ (as is the case for our estimates here) one still should expect $\psi_Y \lesssim 0.01$. Equations (4) and (7) result in the following expression for Yarkovsky-induced outward mass accretion rate at $R_s$:

$$\dot{M}_{Y,s} = \frac{2\sqrt[2]{2}\sqrt[3]{3}}{3}\psi_Y \frac{\sigma R_s^2 T_s^4}{c (GM_s)^{3/2}}$$

$$\approx 2.4 \times 10^{9} \text{ g s}^{-1}\sqrt[3]{\psi_Y} \frac{R_s^2 T_s^4}{0.01 M_s^{1/2}} \frac{T_s}{1500 \text{ K}}. \quad (17)$$

This is somewhat higher than $\dot{M}_{PR,s}$, thanks to the high adopted $\psi_Y = 10^{-2}$ exceeding $\psi_{PR}$, see Equation (8). However, this estimate may be very optimistic because of our poor knowledge of material properties and sizes of disk particles.

Finally, we note that observations do not reveal the existence of metal-poor WDs with debris disks around them, which could plausibly exist if outward migration of particles due to the Yarkovsky force were effective at stopping the PR-driven inward mass accretion. This provides additional evidence that Yarkovsky effect does not play a significant role in the circum-WD debris disk evolution.

3. COMPARISON WITH OBSERVATIONS

We now compare our theoretical predictions with data on $M_Z$ inferred from observations$^2$ of metal-rich WDs. In Figure 2, we plot the values of $M_Z$ from Farihi et al. (2009, 2010) versus stellar effective temperature $T_s$ separately for WDs with and without debris disks detected via IR excesses. We also plot our analytical prediction for $M_{PR,s}$ ($T_s$) for different values of $R_s$ and $T_s$.

It is easy to see from Figure 2 that all systems with detected debris disks exhibit $M_Z$ higher than $M_{PR,s}$. This is very encouraging since whenever WD is orbited by particulate disk one expects PR drag to set a lower limit of the mass flux at the level of $M_{PR,s}$. This lower bound on $M_Z$ is hard (if at all possible) to avoid. This constraint naturally explains a strong positive correlation between $M_Z$ and the rate of disk occurrence found by Farihi et al. (2010): the fraction of stars with compact debris disks is significantly higher for WDs with high $M_Z$ simply because systems with disks cannot have low $M_Z < M_{PR,s}$. This strongly suggests that the PR drag indeed plays an important and visible role in circum-WD debris disk evolution.

It is worth emphasizing that the lack of disk-hosting systems at low $M_Z$ is not caused by some observational bias: disk-bearing WDs with $M_Z \sim M_{PR,s}$ such as GD 16 (Farihi et al. 2009), GD 56 (Jura et al. 2009a), and G166-58 (Farihi et al. 2008) have (sometimes highly) significant detections of IR excesses by Spitzer.

It is also clear from Figure 2 that there are metal-rich systems both with and without disks, in which $M_Z$ significantly exceeds

$^2$ These estimates are somewhat model dependent, see Jura et al. (2009b).

Figure 2. Mass accretion rates of high-Z elements $M_Z$ inferred from elemental abundances measured in WD atmospheres. Metal-rich WDs without debris disks around them (with no detected IR excess) are depicted as crosses and WDs with disks are displayed by open points. Curves show analytical prediction for $M_{PR,s}$ (for different WD radii $R_s$ and sublimation temperatures $T_s$) given by Equation (13). Note that all WDs with disks tend to lie above $M_{PR,s}$ curve, implying that whenever a debris disk is present the Poynting–Robertson drag sets a lower limit on the mass accretion rate.

(A color version of this figure is available in the online journal.)

$\dot{M}_{PR,s}$ for a given $T_s$, sometimes by several orders of magnitude. The most dramatic case is that of DAZB WD GD 362 which has $M_Z \approx 2.5 \times 10^{-10} \text{ g s}^{-1}$ (Farihi et al. 2009), exceeding $\dot{M}_{PR,s}$ corresponding to its $T_s = 10,500 \text{ K}$ by a factor of $\gtrsim 300$. Existence of such objects clearly implies that at least in some cases an additional accretion mechanism must operate on top of the PR drag, giving rise to very high $M_Z$. We suggest such a mechanism that naturally operates in the presence of a debris disk in Rafikov (2011).

Systems without detected debris disks tend to occupy a broad range of $M_Z$, both above and below $M_{PR,s}$. They may be interpreted as WDs that were orbited by compact debris disks in the recent past but have now completely (or largely) lost their disks to accretion. Without an active external source, metals sediment out from atmospheres of these WDs resulting in lower inferred $M_Z$ in systems that had longer time since their debris disk disappearance.

Lifetime of a debris disk of mass $M_d$ accreting via the PR drag alone can be estimated as $M_d/M_{PR} \approx 2-4 \text{ Myr}$ for $M_d = 10^{-2} \text{ g}$ (roughly corresponding to the mass of 200 km asteroid) and $M_{PR}$ typical for a WD with $T_s = 10^4 \text{ K}$. This estimate only marginally agrees with observational constraints suggesting a several $10^5 \text{ yr}$ disk lifetime (Farihi et al. 2009). However, one should keep in mind that this is an upper limit on the lifetime that is realized if no other processes apart from the PR drag drive accretion of solids through the disk.

4. DISCUSSION

In conclusion, we would like to emphasize the robust nature of the mass accretion due to PR drag. Our estimate (13) of $M_{PR,s}$ depends neither on the disk properties such as $\Sigma_0$ (as long as
τ∥ ≳ 1) or $M_f$ nor on the material properties of its constituent particles. Also, $M_{PR,s}$ does not vary much as $T_s$ or $R_*$ change within reasonable limits.

Walker & Mészáros (1989) have previously suggested that rapid rotation of the central object can suppress the PR drag on the surrounding disk. However, it is easy to demonstrate that even if the WD rotates at breakup speed, the amount of angular momentum carried by photons absorbed by the disk is still small compared with the angular momentum that the disk loses via the PR drag.

One may worry that our calculation essentially disregards the details of the particle sublimation process. However, $M_{PR,s}$ is set by stellar illumination outside the innermost annulus of directly exposed particles at the inner edge of the disk (see Section 2.1). Their sublimation is irrelevant and our calculations are robust. Interior of that point, $M_Z$ does not change by continuity and, as a result, the mass accretion rate ends up being insensitive to exactly how directly exposed particles sublimate.

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REFERENCES

Bottke, W. F., Jr., Vokrouhlický, D., Rubincam, D. P., & Nesvorný, D. 2006, Ann. Rev. Earth Planet. Sci., 34, 157
Burns, J. A., Lamy, P. L., & Soter, S. 1979, Icarus, 40, 1
Cuzzi, J. N., et al. 2010, Science, 327, 1470
Dupuis, J., Fontaine, G., Pelletier, C., & Wesemael, F. 1993, ApJS, 84, 73
Ehrenreich, D., et al. 2011, A&A, 525, 85
Elsner, R. F., & Lamb, F. K. 1977, ApJ, 215, 897
Farhi, J., Jura, M., Lee, J.-E., & Zuckerman, B. 2010, ApJ, 714, 1386
Farhi, J., Jura, M., & Zuckerman, B. 2009, ApJ, 694, 805
Farhi, J., Zuckerman, B., & Becklin, E. E. 2008, ApJ, 674, 431
Friedjung, M. 1985, A&A, 146, 366
Gänsicke, B. T., Marsh, T. R., Southworth, J., & Rebassa-Mansergas, A. 2006, Science, 314, 1908
Graham, J. R., Matthews, K., Neugebauer, G., & Soifer, B. T. 1990, ApJ, 357, 216
Jura, M. 2003, ApJL, 584, L91
Jura, M., Farhi, J., & Zuckerman, B. 2007, ApJ, 663, 1285
Jura, M., Farhi, J., & Zuckerman, B. 2009a, AJ, 137, 3191
Jura, M., Muno, M. P., Farhi, J., & Zuckerman, B. 2009b, ApJ, 699, 1473
Klein, B., Jura, M., Koester, D., Zuckerman, B., & Melis, C. 2010, ApJ, 709, 950
Ohtsuki, K., & Toyama, D. 2005, AJ, 130, 1302
Rafikov, R. R. 2011, arXiv:1102.4343
Roy, R. F., Beck, A. E., & Touloukian, Y. S. 1981, in Physical Properties of Rocks and Minerals, Vol. II-2, ed. Y. S. Touloukian & C. Y. Ho (New York: McGraw-Hill), 468
Salmon, J., Charnoz, S., Crida, A., & Brahic, A. 2010, Icarus, 209, 771
Salo, H. 1987, Icarus, 70, 37
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Vokrouhlický, D. 1998, A&A, 335, 1093
Vokrouhlický, D. 1999, A&A, 344, 362
Walker, M. A., & Mészáros, P. 1989, ApJ, 346, 844
Zuckerman, B., & Becklin, E. E. 1987, Nature, 330, 138
Zuckerman, B., Koester, D., Melis, C., Hansen, B. M. S., & Jura, M. 2007, ApJ, 671, 872