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Magnetospherically-trapped dust and a possible model for the unusual transits at WD 1145+017

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ABSTRACT

The rapidly evolving dust and gas extinction observed towards WD 1145+017 has opened a real-time window onto the mechanisms for destruction-accretion of planetary bodies onto white dwarf stars, and has served to underline the importance of considering the dynamics of dust particles around such objects. Here it is argued that the interaction between (charged) dust grains and the stellar magnetic field is an important ingredient in understanding the physical distribution of infrared emitting particles in the vicinity of such white dwarfs. These ideas are used to suggest a possible model for WD 1145+017 in which the unusual transit shapes are caused by opaque clouds of dust trapped in the stellar magnetosphere. The model can account for the observed transit periodicities if the stellar rotation is near 4.5 h, as the clouds of trapped dust are then located near or within the co-rotation radius. The model requires the surface magnetic field to be at least around some tens of kG. In contrast to the eccentric orbits expected for large planetesimals undergoing tidal disintegration, the orbits of magnetospherically-trapped dust clouds are essentially circular, consistent with the observations.

Key words: circumstellar matter— stars: individual (WD 1145+017)— white dwarfs

1 INTRODUCTION

Evolved planetary systems orbiting white dwarfs provide unique and complementary information to conventional planetary system studies. Transit and radial velocity searches yield the frequency, minimum masses, and sizes for closely orbiting planets, where small and likely rocky planets can sometimes be identified with confidence (Gillon et al. 2016), but generally these data are insufficient (Rogers 2015). Despite the large datasets of planetary system frequencies, architectures, planet sizes and even densities, the only empirical knowledge on planet compositions relates to their atmospheres, and only for those systems that are amenable to transit or direct spectroscopy (Sing et al. 2016; Chilcote et al. 2017).

The compositions of the most intriguing worlds, the small and rocky planets where knowledge of their surfaces is key to their habitability, remain firmly out reach via conventional observation. Fortunately, white dwarfs accreting planetary debris are common (Zuckerman et al. 2010; Koester et al. 2014), as evidenced by the observed correlation between atmospheric heavy elements and infrared emission from closely-orbiting dust, usually taken to be in the form of disks (von Hippel et al. 2007; Farihi et al. 2009). These systems distill the infalling planetary debris via atmospheric pollution, and provide powerful insight into the mass and bulk chemistry of the parent bodies (Klein et al. 2010; Gänsicke et al. 2012). For the handful of systems with detailed measurements, nearly all are consistent with distinctly terrestrial-like, differentiated parent bodies (Jura et al. 2013; Jura & Young 2014), a few objects show evidence for water or hydrated minerals (Farihi et al. 2013; Raddi et al. 2015; Farihi et al. 2016), and one apparently ice-rich object (Xu et al. 2017).

This general picture is now rather compelling with more than a decade of corroborating, multi-wavelength observations (Gänsicke et al. 2006; Jura et al. 2007), including the detection of deep and irregular transits at WD 1145+017[1] (Vanderburg et al. 2015; Gänsicke et al. 2016). Theoretical work has been carried out for disk evolution and accretion in these systems (Rafikov 2011; Metzger et al. 2012), and for post-main sequence, dynamical instabilities that may perturb planetesimals onto star-grazing orbits (Veras et al. 2013; Frewen & Hansen 2014). But while simple models can tidally fragment bodies interior to the Roche limit (Debes et al. 2012; Veras et al. 2014), the resulting highly eccentric rings require Myr timescales or longer to shrink and circularize via stellar radiation (Veras et al. 2015), as the bulk of the debris mass for dust production will be contained in cm-size or larger particles

[1] A modest quality spectrum of WD 1145+017 taken prior to 1990 appears to show Ca II K (Berg et al. 1992). If correct, this system has been actively polluted for well over a quarter century.

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(Wyatt 2008). One scenario likely involves mutual collisions – especially near periastron – and gas drag from sublimated material (Farihi et al. 2012; Brown et al. 2017).

The detection of transits towards WD 1145+017 is consistent with the basic picture outlined above, as this star is dusty and enriched with numerous heavy elements (Vanderburg et al. 2015). Quasi-periodic behavior is observed in both *K2* and ground-based transit light curves, mostly centered around 4.5 h but with substantial variations (and uncertainty), and varying interpretations (Rappaport et al. 2016; Gary et al. 2017; Croll et al. 2017). It is noteworthy that individual bodies are not inferred to be the cause of the extinguished light, but rather sizable clouds of debris – several times the size of the Earth (Gänsicke et al. 2016) – that are presumed to be associated with orbiting planetary bodies or fragments. Significant columns of metal-rich gas are also seen in absorption, and which vary on minute- to month-long timescales similar to the overall behavior of the light curve (Xu et al. 2016; Redfield et al. 2017).

A distinct challenge to the canonical model of tidal disruption is the apparent orbits of the transiting debris clouds. The Keplerian orbit for a 4.5 h period around a typical white dwarf is just inside $1.2\,R_\odot$, but any significant eccentricity would result in catastrophic fragmentation for 1000 km bodies (Brown et al. 2017). For example, a rubble pile of this size and $\rho \approx 3-4\,\mathrm{g\,cm^{-3}}$ should totally disrupt within 1 yr unless $e \lesssim 0.1$ (Veras et al. 2017), but the circularization of such an object is non-trivial by tidal forces (Veras 2016).

Motivated by these considerations and others, this paper investigates the possibility that such obscuring clouds are made of small dust grains, trapped in the white dwarf magnetosphere. Section 2 outlines the physical processes required for dust grains to be strongly influenced by the stellar magnetic field. It is shown that, in general, the smaller, infrared emitting grains are likely to be strongly affected by stellar magnetism for surface fields of around a few tens of kG. In Section 3 these ideas are applied to WD 1145+017, where it is proposed that the 4.5 h photometric periodicities be co-identified with the stellar rotation period. An estimate is then made for the surface field strength required to ensure that small dust grains can be trapped close to the co-rotation radius. Section 4 presents the discussion and conclusions.

2 DUST TRAPPING MODEL

Consider the influence of the white dwarf magnetic field on dust in its vicinity, where a typical relevant dust grain has size $a = 1\,\mu\mathrm{m}$, and hence a radius of $r_\mathrm{g} = a/2 = 0.5\,\mu\mathrm{m}$. The initial assumption is that the grain is spherical. This is likely a poor approximation and the effect of this assumption is considered later. Taking the grain density to be $\rho_\mathrm{g} = 3\,\mathrm{g\,cm^{-3}}$, the mass of the dust grain is

$$m_\mathrm{g} = 1.6 \times 10^{-12} \left(\frac{a}{1\,\mu\mathrm{m}}\right)^3 \left(\frac{\rho_\mathrm{g}}{3\,\mathrm{g\,cm^{-3}}}\right)\ \mathrm{g}. \tag{1}$$

2.1 Grain charge

To quantify the interaction between dust grains and the stellar magnetic field, the charge on a typical dust grain needs to be estimated, written here as Ze, where $-e$ is the charge of an electron. The dust grains will likely be ionized by the impact of ultraviolet photons causing the expulsion of electrons (Horanyi 1996). The actual charge is therefore caused by a balance between the rate of impact of suitable photons and the rate at which electrons recombine with the dust grain. It is assumed that the rate of impact of sufficiently energetic photons dominates, and that the grain reaches its maximum charge Z_max for which the electric potential of the grain surface prevents further expulsion of electrons by ultraviolet photons.

The model assumes the grain material has a work function of $\approx 5\,\mathrm{eV}$ (see e.g. Horanyi 1996). Thus one can estimate that typical ultraviolet photons from the white dwarf with energies $\approx 10\,\mathrm{eV}$ are able to expel electrons, provided that the net charge on the grain is such that the surface potential ϕ_g is less than around 5 eV. These numbers are approximate, but will suffice for an initial estimate. Again assuming the grain to be spherical, the surface potential is given by

$$\phi_\mathrm{g} = \frac{Ze}{r_\mathrm{g}}, \tag{2}$$

where Z is the charge on the grain in units of electron charge.

The spare energy given to the dislodged electron cannot exceed $e\phi_\mathrm{g}$, the energy needed to escape the surface positive charge, and thus the maximum value of Z comes from setting $e\phi_\mathrm{g} = 5\,\mathrm{eV}$. The charge on the grain is then

$$Z_\mathrm{max} = 1700 \left(\frac{a}{1\,\mu\mathrm{m}}\right) \left(\frac{e\phi_\mathrm{g}}{5\,\mathrm{eV}}\right). \tag{3}$$

It is noteworthy that this is only an estimate, and likely to be somewhat uncertain. For this reason the dependence on $e\phi_\mathrm{g}$, or equivalently on Z_max, is carried through the analysis.

2.2 Gyro-radius of the grains

For the magnetic field to have an influence on the dust dynamics, to a first approximation the gyro-radius R_G of the dust grain must be comparable to, or smaller than, the radius at which the dust finds itself (cf. Osten et al. 2013). The gyro-frequency is $\Omega_\mathrm{G} = ZeB/m_\mathrm{g}c$, and thus the gyro-radius is given by

$$R_\mathrm{G} = \frac{m_\mathrm{g} c u_\perp}{ZeB}, \tag{4}$$

where $u_\perp$ is the particle velocity perpendicular to the field line.

2.3 Field strength

The model adopts a canonical surface magnetic field for the white dwarf of $B_* = 10^3$ G (cf. Aznar Cuadrado et al. 2004), and a canonical white dwarf radius and mass of $R_* = 10^9$ cm and $M_* = 0.6\,M_\odot$. Assuming a dipolar field, at a distance of $r = 1\,R_\odot$ the magnetic field strength would be

$$B = 3.0 \times 10^{-3} \left(\frac{B_*}{1\,\mathrm{kG}}\right) \left(\frac{R_*}{10^9\,\mathrm{cm}}\right)^3 \left(\frac{r}{R_\odot}\right)^{-3}\ \mathrm{G}. \tag{5}$$

2.4 Velocity

In the worst case scenario, the velocity of a dust grain will be the escape velocity

$$u = \left(\frac{2GM}{r}\right)^{1/2} = 4.8 \times 10^7 \left(\frac{M_*}{0.6\,M_\odot}\right)^{1/2} \left(\frac{r}{R_\odot}\right)^{-1/2}\ \mathrm{cm\,s^{-1}}, \tag{6}$$

with $u_\perp = fu$, and where the factor $f \leqslant 1$ tracks the assumptions about $u_\perp$.

2.5 Magnetic dust radius

Putting the above together, the gyro-radius is now given by

$$R_G = 9.0\times10^{13}\left(\frac{\rho_g}{3\,\mathrm{g\,cm^{-3}}}\right)\left(\frac{a}{1\,\mu\mathrm{m}}\right)^2\left(\frac{r}{R_\odot}\right)^{5/2} f\left(\frac{M_*}{0.6\,M_\odot}\right)^{1/2} \left(\frac{B_*}{1\,\mathrm{kG}}\right)^{-1}\left(\frac{R_*}{10^9\,\mathrm{cm}}\right)^{-3}\left(\frac{e\phi_g}{5\,\mathrm{eV}}\right)^{-1}\ \mathrm{cm}. \quad (7)$$

More useful is the ratio

$$\frac{R_G}{r} = 1.3\times10^{3}\left(\frac{\rho_g}{3\,\mathrm{g\,cm^{-3}}}\right)\left(\frac{a}{1\,\mu\mathrm{m}}\right)^2\left(\frac{r}{R_\odot}\right)^{3/2} f\left(\frac{M_*}{0.6\,M_\odot}\right)^{1/2} \left(\frac{B_*}{1\,\mathrm{kG}}\right)^{-1}\left(\frac{R_*}{10^9\,\mathrm{cm}}\right)^{-3}\left(\frac{e\phi_g}{5\,\mathrm{eV}}\right)^{-1}. \quad (8)$$

Because $R_G/r \propto a^2$, at a given radius, smaller grains are affected more strongly than larger ones.

It is noteworthy that in general $f = u/u_{\rm esc} < 1$. For example, grains on circular orbits have velocities $u_{\rm circ} = (1/\sqrt{2})u_{\rm esc}$. And in general grain trajectories will not be perpendicular to the magnetic field lines. Thus typically one might expect that $f \simeq 1/2$.

For the trajectory of a grain to be substantially affected by the stellar magnetic field, the model requires and sets $R_G/r \leqslant 1$. A radius $r_{\rm magdust}$ can now be defined, within which the dust is strongly influenced by the field. This yields

$$\frac{r_{\rm magdust}}{R_\odot} = 8.4\times10^{-3}\left(\frac{\rho_g}{3\,\mathrm{g\,cm^{-3}}}\right)^{-2/3}\left(\frac{a}{1\,\mu\mathrm{m}}\right)^{-4/3} f^{-2/3} \left(\frac{M_*}{0.6\,M_\odot}\right)^{-1/3}\left(\frac{B_*}{1\,\mathrm{kG}}\right)^{2/3}\left(\frac{R_*}{10^9\,\mathrm{cm}}\right)^{2}\left(\frac{e\phi_g}{5\,\mathrm{eV}}\right)^{2/3}. \quad (9)$$

From these estimates, it is clear that the stellar magnetic field is likely to be important on the relevant scales. Grains with sizes in the range $a \sim 0.1-1$ µm have been inferred to dominate the observed *Spitzer* fluxes of dusty white dwarfs (Reach et al. 2009; Jura et al. 2009). For such grains, with $f \simeq 0.5$ and surface magnetic fields of a few tens of kG (Aznar Cuadrado et al. 2004), the stellar magnetosphere readily extends out to $r \approx 0.2\,R_\odot$, and for sub-micron grains to radii beyond $\approx 1\,R_\odot$. These distance scales correspond to the inner regions of flat disk models (Farihi 2016), and the Roche limit (Veras et al. 2014), respectively, and within which dust production is likely to occur.

However, there are two reasons why this is likely to be an underestimate.

(i) *Grain shape.* The above assumes that grains are spherical, and hence for a given mass this makes the grain as small as possible. Yet, the observed polarization of starlight passing through dust demands that grains are non-spherical (Draine & Fraisse 2009). Thus, for non-spherical dust grains of a given mass, the effective radius r_g is underestimated. This in turn implies an underestimate of the grain size relevant for ionizing photons, hence underestimating possible grain charge, because for a fixed surface potential, the larger the grain, the more charge it can hold.

Therefore, from consideration of the actual structure of grains, it is expected that r_g could be a factor of a few to several larger, or B_* could be similarly smaller than implied by the above calculation.

(ii) *Velocity – the value of f.* Taking the factor $f = 1$ implies that the dust grain velocity relative to the magnetic field is the escape velocity ($u = u_{\rm esc}$), and that the dust grain is moving perpendicular to the magnetic field ($u = u_\perp$). As discussed above in Section 2.5, it is expected that $f < 1$ in general, and a more typical value is $f \simeq 0.5$. This is the relevant value if the velocity were Keplerian, and if the dust particle were moving at 45° to the magnetic field. All else being equal, the size of dust grains scales as $a \propto f^{-1/2}$.

But likely the largest effect occurs if the white dwarf is rotating. Thus for grains in a Keplerian orbit at radius $r = R_\Omega$, one expects $f \ll 1$. In other words, grains are most likely to be trapped by the field at radii close to where their intrinsic velocities are comparable to the local velocity of the magnetic field. Thus there is a strong tendency to trap co-rotating grains.

Therefore stellar magnetic fields are likely to play an important role in the dynamics of dust accretion in many of these systems.

3 APPLICATION TO OBSCURATIONS AT WD 1145+017

These ideas are now applied to obscuration events such as the observed light curve of WD 1145+017, based on the simple idea that the dipping behavior is caused by clouds of dust. To date, these individual clouds of dust have been assumed to originate from (potentially drifting) asteroid fragments in orbit around the star (Rappaport et al. 2016), where the $P \simeq 4.5$ h periodic behavior within the light curve has been interpreted as an orbital period for the asteroid fragments (Vanderburg et al. 2015). A circular orbit with that period is located at a radius of R_Ω where

$$R_\Omega = (GM_*)^{1/3}\left(\frac{P}{2\pi}\right)^{2/3} = 8.1\times10^{10}\left(\frac{M_*}{0.6\,M_\odot}\right)^{1/3}\left(\frac{P}{4.5\,\mathrm{h}}\right)^{2/3}\ \mathrm{cm}. \quad (10)$$

From Equation 8, the smaller dust grains are those that are more likely to be affected by the stellar magnetic field. Croll et al. (2017) indicate that dust grains with sizes either $a > 0.30$ µm or $a < 0.12$ µm would fit their multicolor photometric data. Based on this, a canonical dust grain size of $a = 0.1$ µm is adopted here.

In order to obtain periodic obscuration signals, the model identifies the light curve period P as the rotation period of the white dwarf, and suggests that the dust clouds are trapped in the stellar magnetosphere. Ideally the dust would be trapped at or slightly interior to the co-rotation radius R_Ω. This is defined as the radius at which a circular Keplerian orbit has the same period as the stellar rotation (Pringle & Rees 1972). An analogous model for periodic photometric variability has been proposed for rapidly rotating, weak-lined T Tauri stars in Upper Sco (Stauffer et al. 2017).

The magnetospheric radius R_B is defined as the radius at which accreting material becomes attached to the magnetic field lines. The significance of the co-rotation radius is that if $R_B \lesssim R_\Omega$, then once accreting material becomes attached to a *radial* field line it can still be accreted onto the star, because gravity exceeds centrifugal force. However, if $R_\Omega \lesssim R_B$, then the accretion flow can be disrupted by the centrifugal force once matter is attached to the field lines.

These ideas were introduced originally in the context of gaseous disk accretion in X-ray binaries. In that case the definition of the magnetospheric radius is relatively straightforward, though somewhat assumption-dependent (Pringle & Rees 1972; Davidson & Ostriker 1973; Ghosh, Pethick, & Lamb 1977). However, for dust accretion such as considered here, the physics is more complicated.

For the proposed model for WD 1145+017 to operate, $R_G \approx kR_\Omega$ is required for grains with sizes in the region of interest, i.e. $a \simeq 0.1$ µm. The parameter k is introduced, and expected to be of order unity, in order to keep track of the approximate nature of where relative to R_Ω the dust might be trapped. Setting the left hand side of Equation 8 to unity, and substituting $r = kR_\Omega$ from Equation 10 into the right hand side of Equation 8, it follows that in order for the dust to be influenced by the magnetic field at the co-rotation radius, the required stellar magnetic field has magnitude

$$B_* = 16 \left(\frac{\rho_g}{3\,\mathrm{g\,cm^{-3}}}\right) \left(\frac{a}{0.1\,\mu\mathrm{m}}\right)^2 f \left(\frac{M_*}{0.6\,M_\odot}\right) \left(\frac{R_*}{10^9\,\mathrm{cm}}\right)^{-3} \left(\frac{e\phi_g}{5\,\mathrm{eV}}\right)^{-1} k^{3/2} \left(\frac{P}{4.5\,\mathrm{h}}\right) \mathrm{kG}. \quad (11)$$

Thus, for stellar surface fields of $B_* \approx 10$ kG and greater, one would nominally expect grains with sizes $a \lesssim 0.1$ µm to be affected at, or around, the co-rotation radius.

However, whilst it has been shown that a field of a few tens of kG can play a role in controlling the trajectories of individual dust particles, a further consideration is the field strength necessary to control the total mass of dust required to provide the observed obscuration towards WD 1145+017.

As a starting point, Croll et al. (2017) suggest that the obscuring clouds are of size $R_o \sim 9.5\,R_\oplus \approx 6.1 \times 10^9$ cm. That work focuses on grain sizes of order $a \sim 0.1$ µm, and typical drops in flux during an event as being ≈ 10 per cent. Using these numbers, the total number of grains in a typical cloud is

$$N \sim 1.5 \times 10^{29} \left(\frac{a}{0.1\,\mu\mathrm{m}}\right)^{-2}. \quad (12)$$

Using Equation (1) for the mass of a grain, the mass of the cloud can now be estimated, and hence its mean density is

$$\rho_{cl} \approx 2.5 \times 10^{-16} \left(\frac{a}{0.1\,\mu\mathrm{m}}\right) \mathrm{g\,cm^{-3}}. \quad (13)$$

In order that the field, B, is sufficiently strong to control such clouds at a radius $r_{cl} = kR_\Omega$, the requirement at that radius is

$$B^2/4\pi \approx \rho_{cl}\, u_{cl}^2, \quad (14)$$

where u_{cl} is the velocity of the cloud, and $u_{cl} \approx 2\pi r_{cl}/P$ is the co-rotating velocity at that radius. Thus the condition becomes

$$B(kR_\Omega) \approx 1.8k \left(\frac{a}{0.1\,\mu\mathrm{m}}\right)^{1/2} \left(\frac{M_*}{0.6\,M_\odot}\right)^{1/3} \left(\frac{P}{4.5\,\mathrm{h}}\right)^{-1/3} \mathrm{G}. \quad (15)$$

This would correspond to a field at the stellar surface given by $B_* = B(kR_\Omega)(kR_\Omega/R_*)^3$, that is

$$B_* \approx 940\, k^4 \left(\frac{a}{0.1\,\mu\mathrm{m}}\right)^{1/2} \left(\frac{M}{0.6\,M_\odot}\right)^{4/3} \left(\frac{P}{4.5\,\mathrm{h}}\right)^{5/3} \left(\frac{R_*}{10^9\,\mathrm{cm}}\right)^{-3} \mathrm{kG}. \quad (16)$$

The conclusion is that for a suitable set of system parameters, a plausible model for the periodic photometric behavior of WD 1145+017 could be based on the concept of dust clouds trapped near the magnetospheric co-rotation radius. As noted above, analogous behaviour is seen elsewhere in stellar systems (Stauffer et al. 2017).

The major problem with this speculative model is with the strength of required surface field. A field of some tens of kG is able to influence the trajectories of individual dust particles out to the co-rotation radius. However, such a field is not able to control dust clouds necessary to provide the observed obscuration out to that radius. However, if the geometry is such that the necessary clouds are able to accumulate at radii slightly smaller that the co-rotation radius, such that for example $k \approx 0.3 - 0.5$, then a surface field of some tens of kG would again be sufficient.

4 DISCUSSION AND CONCLUSIONS

This work has shown that the interaction between dust and stellar magnetospheres is likely to be an important physical effect in contributing to the understanding of the dynamics of circumstellar debris around white dwarf stars. Such considerations are already known to be important in the understanding of accretion of gaseous material onto many other types of stellar object including:

(i) accretion onto magnetic neutron stars as models for X-ray pulsars (Lewin & van der Klis 2006);

(ii) accretion onto magnetic white dwarfs as models for AM Her stars (polars) and DQ Her stars (intermediate polars) (Warner 1995);

(iii) accretion onto T Tauri stars (Johns-Krull 2007).

In all these cases the interaction between the accretion flow and the stellar field at the magnetospheric radius is poorly understood, but the interactions are known to be highly unstable and result in variable accretion flux from the stellar surface (Pringle & Rees 1972; Davidson & Ostriker 1973; Arons & Lea 1976a,b; Ghosh, Pethick, & Lamb 1977; Arons & Lea 1980). In the cases of white dwarfs (Kuijpers & Pringle 1982) and of neutron stars (Morfill et al. 1984) it has been suggested that clumps form in the flow at the magnetosphere, and that these clumps arrive as distinct entities at the stellar surface.

In the case discussed here, the interaction at the magnetosphere is even more complicated because the dust flow is likely not hydrodynamic and is more akin to a marginally collisional plasma. Estimates of the mean free paths of the relevant dust grains can be obtained by considering the optical depths of the clouds, and the tendency of the small grains to form clouds may be related to the shortened mean free paths in density enhancements. Nevertheless, predicting the nature (sizes and masses) of the dust clouds that are likely to form is beyond the scope of this paper.

In summary, it has been demonstrated that a stellar magnetic field of a few tens of kG can strongly influence the dynamics of dust particles within the tidal truncation zone. Moreover, it is important to note that these magnetic interactions are most important for the dust particles with sizes $a \lesssim 1$ µm, which are those likely to contribute most to the observed infrared emission. The larger and more massive dust particles – carrying the bulk of the debris mass – are essentially unimpeded.

4.1 WD1145+017

These general ideas have been used to construct a tentative model to explain the periodic photometric behaviour of the polluted white dwarf WD 1145+017. For this model to work, the following is required:

(i) The stellar rotation period must be approximately equal to the period of the observed dipping events, that is $P \approx 4.5$ h. There are currently more than one dozen isolated white dwarfs with rotation periods of less than 5 h, as measured via periodic light curve modulations or asteroseismology (e.g. Hermes et al. 2017). Intriguingly, a significant fraction of these are magnetic (Kawaler 2015), but this may be a selection bias as starspots readily allow the detection of rotation period, which is otherwise challenging for the bulk of white dwarfs.

(ii) The line of sight to the white dwarf needs to lie in or near the (rotational) equatorial plane of the white dwarf. This is because the clouds of dust held up by centrifugal force at the magnetosphere are likely to accumulate close to the equatorial plane. Similarly, those dust particles trapped in the magnetosphere, but closer to the spin axis, do not feel the full effects of centrifugal force and are able to accrete more easily. Note that because of the nature of the scattering process which is thought to bring the planetesimal debris into the sphere of influence of the central white dwarf, there is no expectation that the spin axis of the white dwarf and the spin axis of any putative dust disk be aligned (e.g. Frewen & Hansen 2014).

(iii) In order to significantly affect the dust dynamics, the surface field of the white dwarf need only be modest, preferably greater than around $B_* \simeq 10 - 50$ kG. Fields of such a magnitude should be detectable with spectropolarimetry (e.g. Landstreet et al. 2012, 2016), although such a detection would not be straightforward given the amount of variable absorbing material around the star, and given that for high-resolution spectra (e.g. Xu et al. 2016) integration times can be comparable to the stellar rotation period.

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