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MEASURING M DWARF WINDS WITH DAZ WHITE DWARFS[1]

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ABSTRACT

Hydrogen atmosphere white dwarfs with metal lines, so-called DAZs, show evidence for ongoing accretion of material onto their surfaces. Some DAZs are known to have unresolved M dwarf companions, which could account for the observed accretion through a stellar wind. I combine observed Ca abundances of the DAZs with information on the orbital separation of their M dwarf companions to infer the mass-loss rate of the M dwarfs. I find that for three of the six known DAZs with M dwarf companions, a stellar wind can plausibly explain the observed accretion on the white dwarfs assuming Bondi-Hoyle accretion of solar abundance stellar winds on the order of 10^{-14} to $10^{-16}\ M_{\odot}\ \mathrm{yr}^{-1}$. The rest of the sample have companions with orbits $\gtrsim$1 AU and require companion mass-loss rates of $>10^{-11}\ M_{\odot}\ \mathrm{yr}^{-1}$. I conclude that there must be an alternative explanation for accretion of material onto DAZs with widely separated companions. The inferred winds for two of the close binaries are orders of magnitude smaller than typically assumed for the angular momentum loss of red dwarf–white dwarf pairs due to magnetic braking from a stellar wind and may seriously affect predictions for the formation rate of CVs with low-mass companions.

Subject headings: circumstellar matter — stars: late-type — stars: winds, outflows — white dwarfs

1. INTRODUCTION

Hydrogen atmosphere white dwarfs with spectral absorption lines due to metals are a potential puzzle for white dwarf evolution. Metals present in the upper atmospheres of white dwarfs with $T_{\mathrm{eff}} < 20{,}000$ K generally diffuse out of the upper atmosphere on timescales ranging from days to 10^6 yr (Paquette et al. 1986). It was therefore expected that white dwarfs with cooling ages $\gg 10^8$ yr should show no detectable metal-line absorption. However, a number of both hydrogen (class DA) and helium (class DB) white dwarfs show the evidence of heavy metals in their atmospheres (classes DAZ and DZ). The initial explanation for metal contamination was the accretion of solar abundance interstellar medium (ISM) material (Dupuis et al. 1992, 1993a, 1993b). But the lack of correlation between white dwarfs and dense ISM clouds, a large number of DAZs residing at $<$70 pc within the Local Bubble, the high inferred accretion rates for DAZs, and the lack of hydrogen in DZ atmospheres makes ISM accretion problematic (Aannestad et al. 1993; Zuckerman & Reid 1998; Zuckerman et al. 2003). Recent surveys of white dwarfs have turned up several new DAZs, and these have been used to put forth a separate ISM accretion argument for within the Local Bubble (Koester et al. 2005; Koester & Wilken 2006). In this case, nearby white dwarfs accrete continuously from clouds of warm, partially ionized ISM.

Other explanations exist, however. The direct accretion of heavy metals through cometary impacts with white dwarfs was invoked to explain the first DAZ, G74-7 (Alcock et al. 1986). This explanation can deliver a moderate amount of material to the white dwarf surface, but it fails to explain high-abundance DAZs with short settling times and dusty disks, such as G29-38 and GD 362, unless a planetary system perturbs a steady supply of material close to the white dwarf (Zuckerman & Becklin 1987; Koester et al. 1997; Holberg et al. 1997; Debes & Sigurdsson 2002; Gianninas et al. 2004).

In a survey of DAs for metal lines, 6 of 10 known unresolved DA+M dwarf systems were DAZs compared to 1/9 for double degenerates and 0/7 for resolved binaries (Zuckerman et al. 2003). This raises the possibility that DAZs may be caused by hitherto unseen stellar or substellar companions that deposit material through a stellar wind onto the surfaces of the white dwarfs. The evidence for apparently single DAZs with unknown companions is thin. Only two known substellar companions to white dwarfs exist, and they occur in widely separated binaries (Zuckerman & Becklin 1992; Farihi & Christopher 2004). This is despite wide searches for unresolved stellar or substellar objects in close orbits (Probst & Oconnell 1982; Zuckerman & Becklin 1992; Dobbie et al. 2005; Farihi et al. 2005). Furthermore, concerted searches of DAZs themselves show that stellar companions are ruled out at all separations and substellar companions ruled out for all but the closest orbital separations (Debes et al. 2005a, 2005b, 2006).

M Dwarf stellar wind mass-loss rates are poorly understood and hard to study—upper limits can only be placed on the nearby M5.5 Proxima Centauri based on X-ray and Lyα studies with upper limits of $6 \times 10^{-14}\ M_{\odot}\ \mathrm{yr}^{-1}$ ($3\ \dot{M}_{\odot}$) and $4 \times 10^{-15}\ M_{\odot}\ \mathrm{yr}^{-1}$ ($0.2\ \dot{M}_{\odot}$), respectively (Wargelin & Drake 2002; Wood et al. 2001). Radio observations with marginal detections and spectroscopic observations of coronal mass ejections from low-mass stars have been used to propose very high mass-loss rates from dwarf stars, which has a theoretical motivation (Mullan et al. 1992; Houdebine et al. 1990; Badalyan & Livshits 1992). These results are controversial, however, and depend on the model assumptions made (Lim & White 1996). The recent results for Proxima Centauri suggest that perhaps M dwarf stars have winds comparable to or smaller than solar-type stars, rather than the larger rates. The strength of young M dwarf winds can affect the lifetime of gaseous material in disks that are important for planet formation and limit the presence of dusty disks (Laughlin et al. 2004; Plavchan et al. 2005). In orbit around white dwarfs, M dwarf winds are important for the origin of cataclysmic variables (Schreiber & Gänsicke 2003).

[1] Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained from the Data Archive at the Space Telescope Science Institute (STScI), which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. These observations are associated with program 10255.

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TABLE 1
CLOSE BINARY PARAMETERS

WD	Period (days)	Orbital Separation (AU)	M_{WD} ($M_\odot$)	M_{RD} ($M_\odot$)	R_{RD} ($R_\odot$)	References
0419−487	0.3037	7.3×10^{-3}	0.47	0.095	0.189	1
1026+002	0.597259	0.013	0.68	0.23	0.25	2
1213+528	0.667579	0.015	0.63	0.36	0.32	3

REFERENCES.—(1) Bruch 1999; (2) Saffer et al. 1993; (3) Shimanskii & Borisov 2002.

Under the assumption that the cause of the metal lines in DAZs is due to M dwarf companions, the stellar wind rates for known DAZ+M dwarf systems can be calculated. These calculations require the known orbits of the M dwarf companions. Three of the known DAZ+M systems have well-known orbital periods and masses, since they are detached transiting systems. The other three have recent *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys (ACS) images that allow orbital information to be estimated.

In this paper I infer the stellar wind mass-loss rates of the M dwarf companions to six DAZ+M dwarf binaries. In § 2 I estimate the orbital semimajor axis for each binary. In § 3 I use the semimajor axes and white dwarf diffusion coefficients to infer the mass accretion rate onto the white dwarfs and thus the mass-loss rate of the companion M dwarfs. Finally, in § 4 I discuss my results.

2. DETERMINING ORBITAL SEPARATIONS

2.1. *Close Binaries*

Three of the six DAZs with companions have previously measured orbital periods, primary, and companion masses. WD 0419−487 is a 0.47 $M_\odot$ white dwarf with a 0.095 $M_\odot$ companion in a 7.3 hr orbit. The spectroscopic survey of DAs that discovered WD 0419−487 noted that there was evidence of a hot spot/accretion disk in the observed spectrum (Zuckerman et al. 2003). I would expect that this object may show a higher accretion rate due to some amount of mass transfer in addition to that caused by a wind. WD 1026+002 is a 0.68 $M_\odot$ white dwarf with a 0.23 $M_\odot$ companion in a 14.3 hr orbit. Finally, WD 1213+528 is a 0.63 $M_\odot$ white dwarf with a 0.36 $M_\odot$ companion in a 16 hr orbit. Table 1 lists the orbital parameters important for my calculations.

2.2. *Widely Separated Binaries*

The remaining three systems have had their radial velocities (RV) measured to an accuracy within a few kilometers per second and show either slow RV trends or none at all (Schultz et al. 1996). These WDs are prime candidates for high spatial resolution imaging in order to determine what their approximate orbital separations are. Recently, a large snapshot survey (Program 10255, PI: D. Hoard) with the *HST* ACS was performed on a large sample of previously unresolved white dwarf+red dwarf pairs, including the three DAZ+M systems that have no orbital information (for first results, see Farihi et al. 2006). Of these three, WD 1049+103 and WD 1210+464 show resolved companions with the ACS data. The third DAZ, WD 0354+463 shows no obvious resolved companion (Farihi et al. 2006).

The STScI pipeline calibrated ACS data for these three WDs was retrieved and analyzed by measuring the centroid positions of the white dwarf and resolved companion. Figure 1 shows the two imaged targets with resolved companions. The data was taken with the High Resolution Camera (HRC) on ACS and so the plate scale for the final geometrically corrected images is $\sim 0\farcs025$ pixel^{-1}. The projected radius was calculated and this was used to estimate an orbital separation assuming a circular orbit.

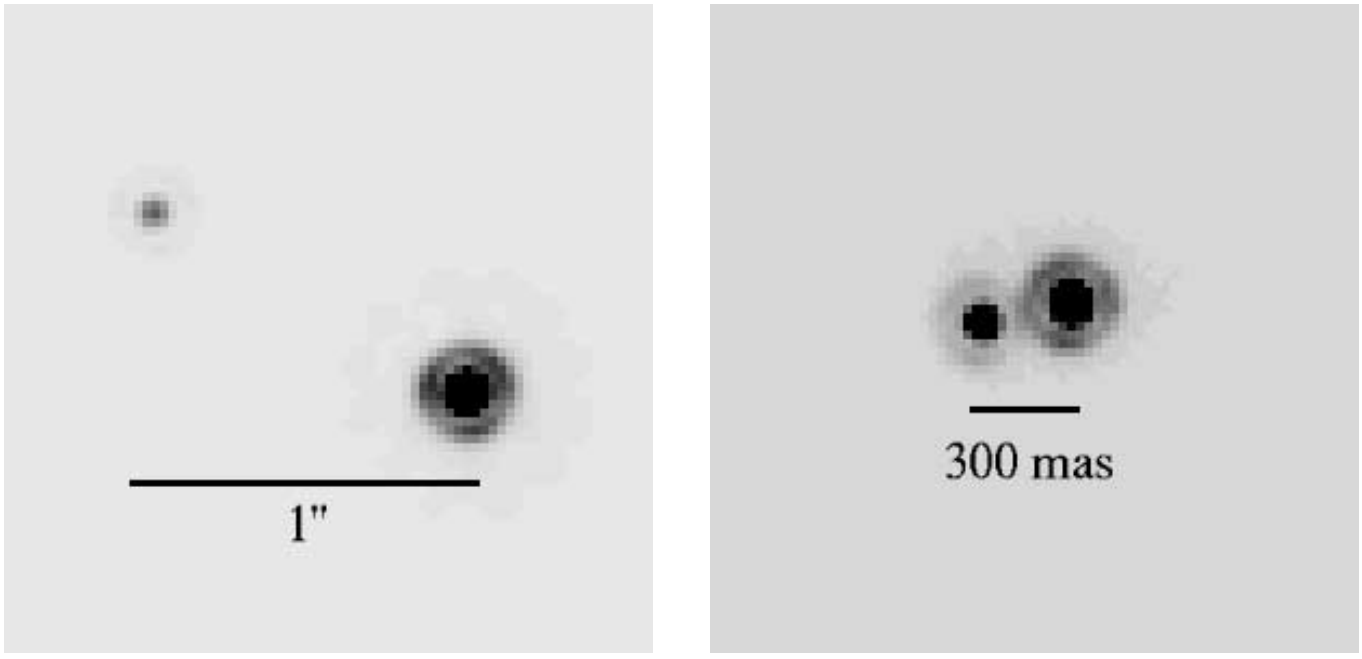


FIG. 1.—*Left*: ACS HRC image of WD 1049+103 with its resolved M dwarf companion. *Right*: ACS HRC image of WD 1210+464 with its resolved M dwarf companion.

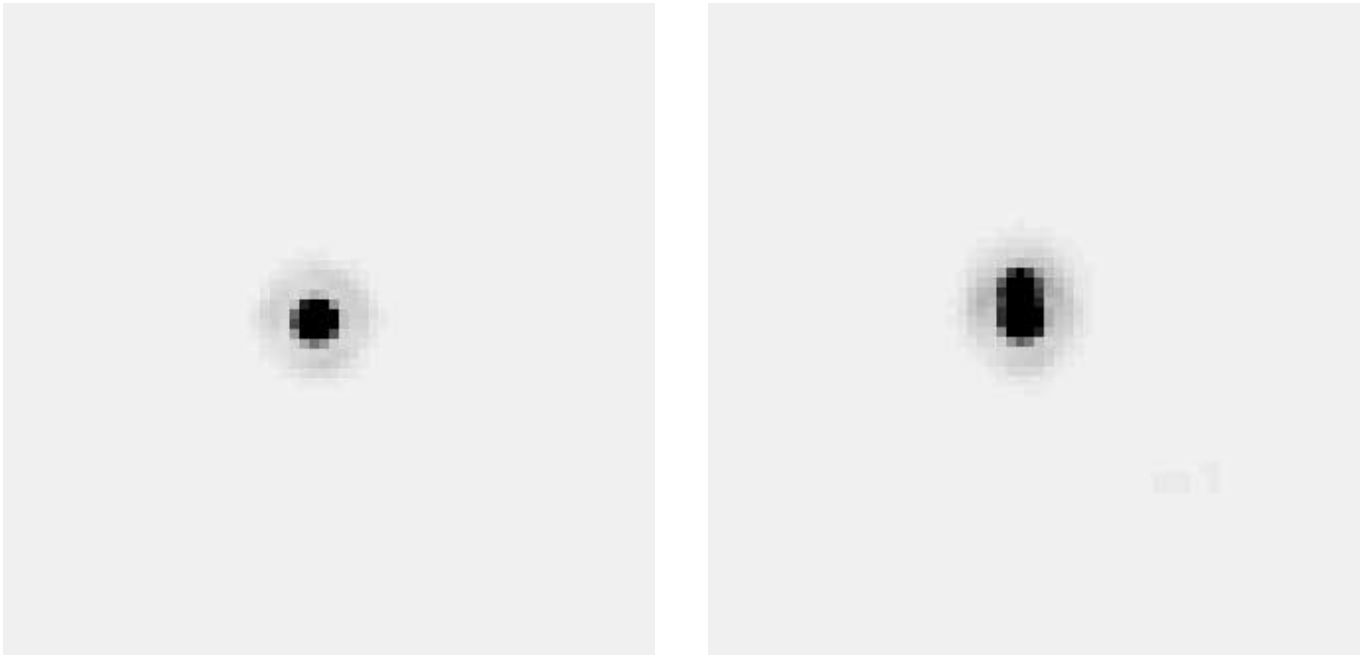


FIG. 2.—*Left*: ACS HRC image of WD 0354+463 without any artificial implants. *Right*: Same image, but with an artificial companion with $m_{F814W} = 15.4$ at a separation of 70 mas.

Since no resolved companion was detected for WD 0354+463, an estimate for the upper limit to the M dwarf orbital separation must be done. One can estimate the sensitivity of an image to a resolved companion by implanting artificial companions into the data and measure when they are recovered. I constructed a reference HRC PSF from the image of WD 1210+464. At separations >70 mas or 2 AU, an object with $m_{F814W} = 15.4$ could have been detected, corresponding to the approximate F814W magnitude expected for both WD 0354+463 and the M dwarf assuming a mass of 0.1 $M_{\odot}$ (Baraffe et al. 1998). Figure 2 shows the limiting separation at which WD 0354+463 would have been observably separated from its companion.

As a lower limit to the orbital separation, I use the timescale of RV observations by Schultz et al. (1996), which is ~0.7 yr. Assuming a primary white dwarf mass of 0.6 $M_{\odot}$, I calculated a lower bound on the orbital separation based on no observed variations. If I assume that at least half a period would have been detected and neglect the mass of the companion, I obtain a lower bound on the orbital semimajor axis of ~1 AU. The projected separation would be ~35 mas, well below the spatial resolution of ACS. I adopt a value of 1.5 ± 0.5 AU for the orbital separation of the M dwarf companion.

Finally, one cannot estimate an orbital separation without knowledge of the white dwarf's distance from the Sun. None of these three objects have parallax measurements, so I utilize the determinations of the distance based on model fits to broadband photometry. WD 0354+463's distance can be calculated by an estimate of its absolute magnitude, which gives a distance of ~30 pc (McCook & Sion 1999). For WD 1049+103 and WD 1210+464, both objects are part of the PG survey, which has been modeled by Liebert et al. (2005). The model distances and the estimated semimajor axes are listed in Table 2.

3. INFERRING MASS ACCRETION AND STELLAR WIND RATES

Inferring the mass accretion onto the white dwarf proceeds from a knowledge of the number abundance of some tracer element relative to hydrogen. In the case of DAZs the strongest observed lines in the visible tend to be the Ca H and K lines. If one assumes a solar composition of material accreted, the accretion rate is then

$$\dot{M} = \frac{qM_{WD}[Ca/H]}{\Theta[Ca/H]_{\odot}}, \quad (1)$$

where q is the mass fraction at the base of the convection zone and Θ is the e-folding timescale for Ca to settle out of the atmosphere (Paquette et al. 1986). $[Ca/H]_{\odot}$ is the solar value of [Ca/H] or 2.1875×10^{-6}. I use the observed number abundances for the DAZs calculated in Zuckerman et al. (2003). For WD 1210+464, there is no abundance calculated, but based on the upper limits based on nondetections of other white dwarfs in that survey, I estimate that $[Ca/H] \sim -7$. I discuss this further in § 4. It should be noted that based on its T_{eff}, WD 1210+464 may be hot enough to sustain a radiative wind, which would create metal lines, thus making it irrelevant that it has a companion. For completeness, I still calculate the inferred mass-loss rate of its companion.

For this paper, I use the values of q determined by Althaus & Benvenuto (1998) and the values of Θ by Paquette et al. (1986) even though these two results use different methods of calculating turbulence. This method has been shown to produce the accretion rate for the DAZ G29-38 reasonably well in light of

TABLE 2
WIDE BINARY PARAMETERS

WD	Angular Separation (arcsec)	Distance (pc)	Orbital Separation (AU)
0354+463	<0.2	30[a]	1.5 ± 0.5
1049+103	0.26	107[b]	28
1210+464	1.04	153[b]	159

[a] McCook & Sion (1999).
[b] Liebert et al. (2005).

TABLE 3
WD Parameters and Derived Mass-Loss Rates

WD	$T_{\rm eff}$ (K)	[Ca/H]	log q	log Θ (yr)	$\dot{M}$ ($M_\odot$ yr^{-1})	$\dot{M}_{\rm RD}$ ($M_\odot$ yr^{-1})
0354+463	7765	−8.335	−8.8	3.37	6×10^{-16}	6×10^{-10}
0419−487	6296	−9.284	−7	4.5	4×10^{-16}	6×10^{-15}
1026+002	14,300	−8.56	−16.6	−2	2×10^{-18}	1×10^{-16}
1049+103	19,800	−7.182	<-18	<-2.2	3×10^{-18}	7×10^{-10}
1210+464	27,000	−7	<-18	<-2.2	4×10^{-18}	5×10^{-8}
1213+528	13,000	−8.1	−16	−0.6	9×10^{-19}	1×10^{-16}
Proxima Centauri						4×10^{-15}, 6×10^{-14}

independent estimations of the accretion rate (Graham et al. 1990; Debes & Sigurdsson 2002). In addition, WD 1049+103 and WD 1210+464 have higher $T_{\rm eff}$ values than those calculated by either method, so I use the values from the highest effective temperatures calculated.

Inferring the mass-loss rate of the companion requires a mechanism for accretion. For simplicity and without knowledge of the exact mechanism for creating a stellar wind, I assume the M dwarf companion expels a spherically symmetric flow at the escape speed from the surface of the M dwarf. I assume that the white dwarf accretes material through a Bondi-Hoyle accretion flow determined by

$$\dot{M} = \frac{4\pi G^2 M_{\rm WD}^2 \rho(R)}{v_{\rm rel}^3}, \tag{2}$$

where G is the gravitational constant, ρ is the density of material surrounding the WD, and v is the relative velocity to the WD at which the gas is passing, which I take to be $\left(v_{\rm wind}^2 + v_{\rm orb}^2\right)^{1/2}$ (Bondi & Hoyle 1944). The escape speed from a low-mass star is $\sim$600 km s^{-1}, assuming that $M/R \sim 1$. It is possible that the widely separated binaries have a higher mass than the close binaries. The mass-radius relation is roughly true for most low-mass stars, as can be seen in Table 1 (but see López-Morales & Ribas 2005). However, WD 0419−487's radius is roughly twice as large as would be expected. This could be related to the possibility of its red dwarf undergoing mass transfer with the white dwarf, or to the fact that it is most likely tidally locked and is a fast rotator. In any case, the assumption of 600 km s^{-1} for an escape speed for the widely separated binaries I am studying is probably safe, since they should be similar to field red dwarfs.

Using the escape speed at the radius of the companion may not be strictly true. For example, one could model isothermal or polytropic winds from the M dwarfs assuming some heating mechanism. This is highly model dependent and requires information about the M dwarf companions that is not easily determined by the observations at hand. Presumably the main source of heating for the companions is comparable to that for the solar wind, where coronal heating provides the bulk of energy for the acceleration of the wind. Uncertainties in v are discussed further in § 4.

In addition, Bondi-Hoyle accretion may not accurately describe these systems. Many astrophysical objects show departures from the simple Bondi-Hoyle picture, such as isolated neutron stars accreting from the ISM (Perna et al. 2003) and supermassive black holes (Di Matteo et al. 2001). In these cases, there are departures from the simple plane parallel geometry of the Bondi-Hoyle case due to turbulence, and magnetic fields (Krumholz et al. 2005). These departures serve to suppress the Bondi-Hoyle accretion rate, making accretion more inefficient. Wind accretion in binary systems as well can depart from the simple Bondi-Hoyle case, particularly when $v_{\rm orb} \sim v_{\rm wind}$. In these cases, the accretion rates can be an order of magnitude lower (Theuns & Jorissen 1993; Theuns et al. 1996). For all of these situations, the accretion suppression results in higher inferred wind mass-loss rates. The values I calculate correspond to strict lower limits if simple Bondi-Hoyle accretion is not present.

The final step is to link the mass-loss rate of the red dwarf to the observed accretion rate onto the WD. The density depends directly on this mass loss. I assume that the mass-loss rate is constant and calculate the density due to the continuity equation (Lamers & Cassinelli 1999):

$$\rho(R) = \frac{\dot{M}_{\rm RD}}{4\pi v R^2}, \tag{3}$$

where $\dot{M}_{\rm RD}$ is the mass-loss rate. The equation can be combined with equations (1) and (2) and solved for $\dot{M}_{\rm RD}$ in terms of known or inferred quantities:

$$\dot{M}_{\rm RD} = \frac{q[{\rm Ca/H}]}{\Theta[{\rm Ca/H}]_\odot} \frac{R^2 v^4}{G^2 M_{\rm WD}}. \tag{4}$$

I tabulate my results for the known close binaries and the resolved binaries in Table 3. For comparison, the solar wind mass-loss rate is $\sim 2 \times 10^{-14}\ M_\odot$ yr^{-1}.

The uncertainties in equation (4) can be roughly quantified. The close binaries have more accurate measures of $\dot{M}$, since $M_{\rm WD}$, R, and [Ca/H] are all known to within a few percent. In their cases the formal statistical error based on these measurements comes to $<$10%. For the widely separated binaries, the errors in $M_{\rm WD}$ and [Ca/H] are on the order of $\sim$10% as well. Assuming that the model parameters and v are correct, $\dot{M}_{\rm RD}$ is well constrained.

Since the results are model dependent, systematic errors most certainly dominate over the statistical errors estimated above. Uncertainty is present in the calculation of Θ, which depends on q, the mass fraction of the convective envelope, the diffusion coefficients within the envelope, and the behavior of the turbulence within the envelope as a function of temperature (see Althaus & Benvenuto 1998, for example). At $T_{\rm eff} > 12{,}000$ and $<$8000 K, the various flavors of turbulence tend to converge within factors of a few, while between these two ranges values for q vary by up to 4 orders of magnitude. This uncertainty is helped somewhat by the fact that $\Theta \propto q^{0.7}$ (Paquette et al. 1986). Equation (4) shows that $\dot{M}_{\rm RD} \propto q^{0.3}$. Thus, an uncertainty of up to 4 orders of magnitude in q corresponds to a uncertainty in $\dot{M}$ of a factor of 15. To self-consistently calculate q and Θ, the same turbulence formalism should be employed to determine both quantities.

Unfortunately, a self-consistent calculation of the diffusion times using different turbulences has yet to be synthesized properly for

the range of temperatures, masses, and atmospheric compositions relevant to cool DAZs, and understanding of the underlying mechanism for forming DAZs would be greatly advanced by an update of this important work (see also Zuckerman et al. 2003). Most of the DAZs in my sample are in the range in which the various models converge well to within factors of 2, so the uncertainty is $q/\Theta \sim 25\%$.

The distance R, determined from the estimated orbital separations can be uncertain for the widely separated binaries. Since these are projected distances, they do not necessarily correspond to the true orbital separation of the pair. However, any such uncertainty would serve to raise the inferred stellar wind mass-loss rate, since the projected orbital separation would always be smaller than the true orbital separation. Conversely, the companions could be in high eccentricity orbits that bring the star much closer than observed. Such a situation would mean that the mass-loss rate would be overestimated. In that case, R would have to change by a factor of 3 (corresponding to an orbital $e \sim 0.5$) to roughly produce an order of magnitude change in $\dot{M}_{\rm RD}$. It is not guaranteed that the resolved companions are physically bound, since there is no common proper motion information—the observations were taken at one epoch. The extremely close separations ($<1''$) and the fact that the blended near-IR photometry are consistent with companions at the same distance makes chance alignments unlikely.

The solar wind velocity is variable, ranging from 60% to greater than the escape speed of the Sun, which implies that v could have a range of values, probably not exceeding a factor of 2. The true velocity of the wind from an M dwarf depends sensitively on the model for that wind, which is beyond the scope of this paper. In the case of the solar wind, the measured velocity at 1 AU is less than that predicted for an isothermal or polytropic wind (Lamers & Cassinelli 1999). Since the inferred mass-loss rate is $\propto v^4$, a change in estimated speed by a factor of 2 would change the calculated mass-loss rates by an order of magnitude.

To sum up, systematic errors in $\dot{M}_{\rm RD} \propto q^{0.3} R^2 v^4$, with v creating the largest systematic uncertainty for the close binaries and R and v creating the largest uncertainties for the resolved systems. The estimates presented in Table 3 are accurate to an order of magnitude for the close binaries, while the resolved binaries are accurate to within 2 orders of magnitude. This is comparable to the range of upper limits given for the mass-loss rate of Proxima Centauri, which approximately spans an order of magnitude.

4. DISCUSSION

Our results break down along the lines of those DAZs with known close companions ($a < 0.02$ AU) and those with greater separations. At smaller separations, the calculated mass-loss rates agree reasonably well with the upper limit to the wind around Proxima Centauri (Wargelin & Drake 2002; Wood et al. 2002). The mass-loss rates I calculate are about 2 orders of magnitude smaller than Proxima Centauri's smaller upper limit, with the exception of WD 0419−487, which is comparable, although larger than the other two M dwarfs. This larger rate could be explained by moderate Roche lobe overflow, evaporation of the companion by the DAZ, or efficient capture of the companion's wind by a magnetic field. If WD 0419−487 were efficiently capturing all of its companion's wind, $\dot{M}_{\rm RD}$ would fall nicely in with those observed for the other two close binaries.

On the other hand, the mass-loss rates determined for the widely separated companions are 3 to 4 orders of magnitude larger than the solar wind. This is despite a slightly higher uncertainty of the accretion rate onto the white dwarfs. Most of these uncertainties would conspire to create a higher accretion rate. For WD 1210+464, a lower accretion rate is possible if the detected equivalent width corresponds to a lower abundance than assumed. However, even at the smallest lower limit of the Zuckerman et al. (2003) survey ([Ca/H] $\sim$ 12.8), the inferred mass-loss rate of the companion would be equivalent to the solar wind and 2 orders of magnitude higher than the close binaries. It is possible that these systems are hierarchical triples, with companions that are undetected by RV observations but in orbits similar to the close binaries. WD 1210+464 and WD1049+103 have F814W photometry consistent with single DAZs, neglecting their resolved companions. This strongly argues that any further unresolved companions would have to be quite dim and of low mass. Conversely, M dwarfs could have the supersolar rates predicted by the earlier results, but in light of the estimated winds of Proxima Centauri and the three close M dwarfs this seems unlikely. Furthermore, given the inferred total ages of the host white dwarfs, the companions would have either completely evaporated or lost a large fraction of their total mass.

The low mass-loss rates for the three closest binaries has two possible interpretations. Either the mechanism for accretion is suppressed relative to Bondi-Hoyle accretion by several orders of magnitude, if one expects M dwarf winds to be similar to the Sun, or M dwarf winds are quenched even in situations in which they are rotating quickly and should have significant activity due to strong magnetic fields. Some evidence for the quenching of winds for low-mass stars comes from Mohanty & Basri (2003), who find that very late spectral-type stars have lower indicators of activity due to a corona or chromosphere. This has been noted in studies of the angular momentum evolution of CVs, where fully convective companions were believed to have lost less angular momentum due to an inefficient dynamo process (Durney et al. 1993).

If the winds from these low-mass companions are orders of magnitude smaller than the solar wind mass-loss rate, this has significant implications for the angular momentum evolution of CV progenitors and CVs themselves. Typically, it has been assumed that the angular momentum evolution of a CV or CV-progenitor occurred due to magnetic braking through a stellar wind, with angular momentum loss:

$$\dot{J} = -K_w \left(\frac{R_{\rm RD}}{R_\odot}\right)^{2-N} \left(\frac{M_{\rm RD}}{M_\odot}\right)^{-N/3} \left(\frac{\dot{M}}{10^{-14}\ M_\odot\ {\rm s}^{-1}}\right)^{1-2N/3},$$

$$\omega^3 \text{ for } \omega \le \omega_{\rm crit},$$

$$= -K_w \left(\frac{R_{\rm RD}}{R_\odot}\right)^{2-N} \left(\frac{M_{\rm RD}}{M_\odot}\right)^{-N/3} \left(\frac{\dot{M}}{10^{-14}\ M_\odot\ {\rm s}^{-1}}\right)^{1-2N/3}, \quad (5)$$

$$\omega\omega_{\rm crit}^2 \text{ for } \omega > \omega_{\rm crit}, \quad (6)$$

where $\omega_{\rm crit}$ represents a cutoff rotation speed where the magnetic field saturates. This equation is a modified form of that used by Kawaler (1988) following the work of Mestel & Spruit (1987) and Weber & Davis (1967). This prescription was used by others to estimate the timescale for the evolution of single low-mass stars, the onset of mass transfer in CV progenitors, and the timescale for the evolution of CVs (Sills et al. 2000; Schreiber & Gänsicke 2003; Andronov et al. 2003). In all of these cases, it was implicitly assumed that the mass-loss rate was approximately the solar wind mass-loss rate. K_w and N were essentially free parameters but were chosen to be 2.7×10^{47} g cm s and 1.5, respectively, in these works. K_w essentially collects all the uncertainties in the properties of the wind and magnetic field of a particular star, and N corresponds to the particular magnetic field geometry. It is immediately apparent that for the given N, $\dot{J} \propto \dot{M}$ and the consequent angular momentum–loss rate for the observed

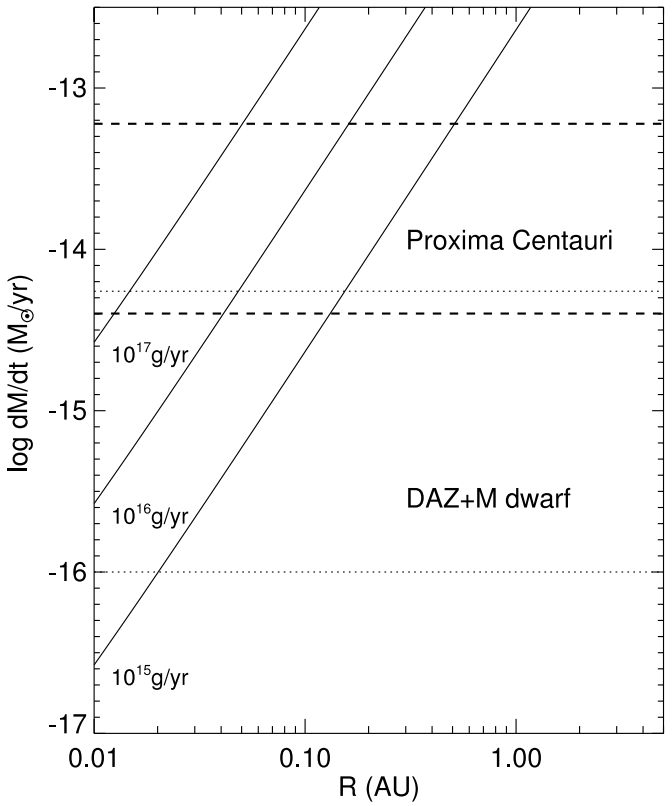


FIG. 3.—Calculation of stellar mass-loss rates for given observed white dwarf accretion rates as a function of distance. Each curve corresponds to a different level of accretion one would observe on a white dwarf. The horizontal dashed lines encompass the range of mass-loss rate values observed as upper limits for Proxima Centauri and the dash-dotted lines encompass the rates calculated for the DAZ+M dwarf sample.

DAZs would be 1–2 orders of magnitude smaller than would be calculated by equation (5). The consequent timescale for these binaries to become CVs would be dominated by gravitational radiation, and would not be affected significantly by magnetic braking.

I also investigate a plausible orbital separation cutoff in which a typical measured WD accretion rate can be maintained by an M dwarf wind. Using a similar calculation to the one I used for my widely separated binaries, I place a cutoff for reasonable mass-loss rates due to winds at the stellar wind upper limits for Proxima Centauri (see Table 3). Figure 3 shows the result for varying levels of mass accretion that should be typical for DAZs. The lowest accretion rates allow plausible companions at wider separations, but the maximum allowed is $\sim$1 AU.

It may be instructive to separate DAZs into three classes for ease of identifying the underlying mechanism for accretion. The first class would be DAZs with companions in orbits $\lesssim$1 AU. These are most plausibly explained by a wind scenario and can be used to measure M dwarf winds to rates orders of magnitude smaller than other methods (Wood et al. 2001, 2002). The second class would encompass all singular WDs and WDs in binaries $\gtrsim$1 AU, with distances from the Sun $<$70 pc. These DAZs cannot easily be explained by either ISM accretion or the companion wind explanation. The third class of DAZs would be at distances $\gtrsim$70 pc and be either singular or have companions at separations $\gtrsim$1 AU. These objects would either have to show ISM accretion through correlation with a known dense cloud or through spectroscopic evidence of a surrounding medium. Otherwise they would have the same origin as those in the second class.

ISM accretion remains viable for the two binaries that are at larger distances, although one would expect these two objects to correspond with known clouds or show some other evidence of a fairly dense ISM component. WD 0354+463, however, is well within the Local Bubble. Both wind accretion and ISM accretion would pose difficulty explaining this object. Planetesimal accretion could still be possible. This can either occur through comet impacts and disruptions, such as suggested by Alcock et al. (1986) and Debes & Sigurdsson (2002), or through the tidal disruption of asteroids, as suggested by Jura (2003). Relic planetesimals from a circumbinary ring around the two stars could provide the necessary materials. The M dwarf could be slowly perturbing the planetesimals. Since extrasolar planets are known to exist in binary systems, the interaction between a planet and M dwarf could be perturbing planetesimals into WD crossing orbits. If this is the case, the reservoir of planetesimals might be detectable with *Spitzer* or at longer wavelengths.

Finally, there are roughly 15 other detached systems with M dwarf companions with orbital information and masses for both the white dwarf and the companion that could be analyzed in the same way (Ritter & Kolb 2003). Medium- to high-resolution optical spectra could be used to find out how many of these objects possess metal lines, and whether the mass-loss rates inferred for those systems match the binaries in my sample.

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