DISKS AND PLANETS AROUND MASSIVE WHITE DWARFS

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ABSTRACT

We predict the existence of dusty disks and possibly CO planets around massive white dwarfs. We show that the thermal emission from these disks should be detectable in the infrared. The planets may also be detectable either by direct infrared imaging, spectroscopy, or using the pulsations of the white dwarfs.

Subject headings: accretion, accretion disks - planetary systems - white dwarfs

1. INTRODUCTION

The recent direct imaging of the companion to the brown dwarf 2MASS J1207334–393254, and the estimates of its mass (two to five Jupiter masses) open a new era in extrasolarplanet research (Schneider et al. 2005; Chauvin et al. 2005). At the same time, *Spitzer* observations are now revealing detailed properties of dusty disks around young stellar objects (e.g., Meyer et al. 2004).

In the present Letter, we propose that disks and planets may be found in an unexpected place—around massive white dwarfs. Our model is presented in § 2, and some observational tests are discussed in § 3.

2. MERGING WHITE DWARFS, PLANETS, AND DUST DISKS

The merger of two white dwarfs is an inevitable outcome of binary star evolution in some binary systems (see, e.g., Iben & Livio 1993 for a review). Liebert et al. (2005) examined a sample of 348 DA white dwarfs (WDs). They found that the mass distribution has three components: (1) a peak centered around 0.6 M_{\odot} , (2) a low-mass component around 0.4 M_{\odot} , and (3) a high-mass component extending above $0.8 M_{\odot}$. The highmass component was estimated to contribute about 15% of the WD formation rate. Liebert et al. (2005) also concluded that most (\geq 80%) of the high-mass objects formed by means of mergers of two lower mass WDs. The merger process itself has been studied in some detail (e.g., Benz et al. 1990; Mochkovitch & Livio 1990). It leads to the total dissipation of the lighter of the two WDs (which fills its Roche lobe first) within a few orbital periods. The dissipated WD material forms a disk around the more massive component, most of which is eventually accreted onto the heavier member to form the massive WDs found by Liebert et al. However, in order for this disk material to be accreted at all, some fraction of the matter in the disk needs to take up the angular momentum. The matter into which the angular momentum is deposited spreads out to form a disk that is much lower in mass, but much larger in radius. Note, however, that the remaining disk is essentially 100% metals, since it typically represents the composition of a CO white dwarf.

To model this process, we start with two identical white dwarfs, each of mass $M_{\rm WD} = 0.5 M_{\odot}$, in a circular orbit around each other and filling their Roche lobes. These merge to give

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a new white dwarf whose mass is essentially equal to $M_{\text{NWD}} = 2M_{\text{WD}} = 1 M_{\odot}$. This implies that if the semimajor axis of the binary is *a*, the mean white dwarf radii are $R_{\text{WD}} = 0.38a$. In this case the orbital angular momentum is

$$J_{\rm orb} = \frac{1}{4} M_{\rm NWD} (GM_{\rm NWD} a)^{1/2}.$$
 (1)

It is straightforward to show that this angular momentum cannot be taken into the spin of the newly formed white dwarf (since the breakup speed would be exceeded by a factor of around 3). We therefore model the ensuing dynamics of the merger as an accretion disk with fixed angular momentum $J_{\rm orb}$ around a central point mass M_{NWD} . The time evolution of such disks is well known (e.g., Pringle 1981, 1991). The exact behavior depends on the details of the dissipative processes within the disk, but at late times the outer radius of the disk expands to take up the angular momentum, and the inner regions behave as a steady accretion disk, but with gradually decreasing accretion rate. In this sense, the disk dynamics can be expected to be akin to that of the usual protostellar disks, in which all the accretion comes from large radii, but at a steadily declining rate. For simplicity we assume that the surface density profile of the disk is of the form

$$\Sigma \propto R^{-\alpha},$$
 (2)

where we require $\alpha < 2$. For example, the usual solar nebula profile is assumed to have $\alpha \approx 3/2$ (Armitage et al. 2002), whereas if we adopt the Lin & Papaloizou (1985) prescription for the viscosity in cool protostellar disks of $\nu \propto \Sigma^2$ we would obtain $\alpha \approx 0$. With this profile, the angular momentum of the disk is given in terms of the disk radius R_d and the disk mass M_d by

$$J_d = \xi M_d (GM_{\rm NWD} R_d)^{1/2},$$
 (3)

where $\xi = (2 - \alpha)/[(5/2) - \alpha]$. We shall adopt $\alpha = 3/2$ and $\xi = 1/2$ as typical parameters.

If we equate the angular momentum of the disk to that of the original binary, we find that the disk mass is given in terms of the disk radius by

$$M_d = 0.81(\xi/\frac{1}{2})^{-1}M_{\rm NWD}(R_{\rm WD}/R_d)^{1/2}.$$
 (4)

We now need to ask at what stage planets might start to form in such a disk. We have already argued that a disk of this sort does not differ in its dynamics greatly from a standard protostellar disk. If this were a disk with standard cosmic abun-

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FIG. 1.—Simulated spectral energy distribution for a 1 AU radius dust disk surrounding a white dwarf. The dashed line is the input stellar spectrum, and the solid lines show the characteristic infrared-excess emission for 10 viewing angles evenly spaced in $\cos i$ (pole-on viewing is the uppermost solid line). At high inclinations, the white dwarf is occulted by the disk and the optical spectrum is all scattered light.

dances, then it might seem reasonable to assume that planetesimal formation sets in when the disk radius exceeds the snow line, which is the radius outside which the disk temperature equals the ice condensation temperature of $T_c \approx 170$ K. But this disk does not have solar composition and, in particular, lacks the hydrogen to produce the water for the "snow." In this situation it seems sensible to adopt the dust grain condensation temperature of $T_c \approx 1600$ K as the equivalent of the snow line. Adopting the temperature profile for an optically thin disk, given by

$$T_d = 2.8 \times 10^2 \left(\frac{R}{1 \text{ AU}}\right)^{-1/2} \left(\frac{L}{1 L_{\odot}}\right)^{1/4} \text{ K},$$
 (5)

gives the condensation radius as

$$R_{\rm dust} = 0.0306 \left(\frac{L}{1 L_{\odot}}\right)^{1/2} \left(\frac{T_c}{1600 \text{ K}}\right)^{-2} \text{ AU.}$$
(6)

Taking the radius of the newly formed white dwarf to be $R_{\text{NWD}} = 6 \times 10^8$ cm, and its temperature to be $T_{\text{NWD}} = 50,000$ K, we find that the dust condensation line occurs at a radius

$$R_{\rm dust} = 0.02 \left(\frac{R_{\rm NWD}}{6 \times 10^8 \text{ cm}}\right) \left(\frac{T_{\rm NWD}}{50,000 \text{ K}}\right)^2 \left(\frac{T_c}{1600 \text{ K}}\right)^{-2} \text{ AU}.$$
(7)

When this radius is reached, the mass in the disk is

$$M_{d} = 0.047 \left(\frac{\xi}{1/2}\right)^{-1} \left(\frac{M_{\rm NWD}}{1 M_{\odot}}\right) \\ \times \left(\frac{0.6R_{\rm WD}}{R_{\rm NWD}}\right)^{1/2} \left(\frac{T_{\rm NWD}}{50,000 \text{ K}}\right)^{-1} \left(\frac{T_{c}}{1600 \text{ K}}\right)^{-1} M_{\odot}.$$
 (8)

Since the mass is concentrated at large radii, we may take this mass as an estimate of the mass available for forming planets.

As the radius expands to ~1 AU, the mass in the disk is ~0.007 M_{\odot} .

In a recent, important work, Fischer & Valenti (2005) have shown that the probability of hosting a planet increases quite dramatically with the metallicity of the host star (approximately as [Fe/H]^{1.8}, where [Fe/H] represents the iron abundance). If this result can be extrapolated to the metallicities under discussion here, it implies that planet formation would be highly efficient in disks of the kind we are considering.

The only other situation we are aware of that is analogous to the planet formation picture we have described above is the formation of planets around the pulsar PSR 1257+12 (Wolszczan & Frail 1992). The planets in this system, presumably around a neutron star of mass $M_{\rm NS} \approx 1.4 M_{\odot}$, move in almost circular orbits and, so, most likely formed in a disk. They have masses of 2.8 $M_{\rm Earth}$ at 0.47 AU and 3.4 $M_{\rm Earth}$ at 0.36 AU. The disk in which the planets formed is thought to have come from the disruption of a low-mass companion (Stevens et al. 1992), of mass $M_2 \approx 0.016 M_{\odot}$ (King et al. 2005). In this case, we calculate that the fraction of the original orbital angular momentum that ended up in these two planets is $f \sim 1\%$. If the planets, being Earth-mass, are also Earth-like, then this implies a high efficiency of converting the initial angular momentum stored in elements heavier than H and He into planets.

3. OBSERVATIONAL CONSEQUENCES

One of the predictions of the proposed scenario is the potential existence of dusty disks around massive WDs. Our calculations suggest that a typical circumstellar dust disk will have a mass and a radius of $M_d \sim 0.007 \ M_{\odot}$ and $R_d \sim 1$ AU, respectively. The disk will be gas-poor and the dust will reprocess radiation from the white dwarf to produce an infrared-excess spectral energy distribution (SED). Figure 1 shows a simulated SED for a dust disk around a white dwarf (assumed to be at a distance of 12 pc, typical of nearby WDs; Holberg et al. 2002), demonstrating that the thermal emission from the disk will be detectable above the white dwarf photosphere at infrared wavelengths (the different plots are evenly spaced in the cosine of the inclination). In this simulation, the white dwarf (after merger) has $M_{\rm NWD} = 1 M_{\odot}$, $T_{\rm NWD} = 5 \times 10^4$ K, and $R_{\rm NWD} =$ 6×10^8 cm, and a Kurucz model atmosphere was used. Using a 5 \times 10⁴ K blackbody did not result in any significant changes. The disk has a dust mass $M_d = 0.007 M_{\odot}$, outer radius $R_d =$ 1 AU, and inner radius corresponding to a dust destruction temperature of 1600 K. The dust opacity and scattering properties are assumed to be those for interstellar dust (e.g., Kim & Martin 1994), which gives the prominent 10 μ m silicate feature in the simulated SED. If the dust in the disk has grown to sizes larger than typical interstellar medium grains, the opacity will be grayer and the silicate features less prominent (e.g., Wood et al. 2002). We assume the dust is in vertical hydrostatic equilibrium and the disk has a radial surface density $\Sigma \sim$ $r^{-3/2}$. The disk temperature, vertical hydrostatic density structure, and emergent SED are computed using the Monte Carlo radiation transfer code described by Walker et al. (2004). If the dust is not in vertical hydrostatic equilibrium and has settled to the midplane, the infrared-excess emission will be less than shown in Figure 1 but will still be detectable above the photosphere and resemble that from a flat reprocessing disk (e.g., Adams et al. 1987). Note that massive WDs are considerably smaller than their low-mass counterparts, and hence, at a given temperature they are less luminous.

Disks that are extremely metal-rich may also be expected to form planets (see also Livio et al. 1992; Kuchner & Seager 2005). Following the pioneering work of Becklin & Zuckerman (1988), a few more extensive searches for planets around WDs have already started. The search methods include infrared imaging, infrared spectroscopy, and the use of WD pulsations. Clarke & Burleigh (2004; see also Burleigh et al. 2002, 2003) describe the first results from a deep infrared imaging $(J \sim 24)$ campaign on 24 WDs. They found two objects that appear to have the same proper motion as the WDs (at least at the 1σ level) and whose luminosities are consistent with masses in the range $(7-10)M_{Jup}$. The Clarke & Burleigh search aims at planets that existed around the WD progenitor, and which have survived stellar evolution. The current Letter identifies massive WDs as high-probability hosts of dusty disks or planets, with these disks and planets having formed during a late evolutionary phase, and having unusual compositions.

A second existing search for planets around WDs uses the pulsations of the WDs as intrinsic clocks (Mullally et al. 2003). The idea here is that hot, DAV-type WDs near 12,000 K pulsate with an extraordinarily stable pulsation period. The reflex orbital motion causes a rate of change P in the period P of order

$$\frac{\dot{P}}{P} = \frac{G}{c} \frac{PM_p \sin i}{r_p^2}$$
(9)

(e.g., Kepler et al. 1991), where G and c are the gravitational constant and speed of light, respectively, and *i* is the orbital

Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 312, 788

- Armitage, P. J., Livio, M., Lubow, S. H., & Pringle, J. E. 2002, MNRAS, 334, 248
- Becklin, E. E., & Zuckerman, B. 1988, Nature, 336, 656
- Benz, W., Bowers, R. L., Cameron, A. G. W., & Press, W. H. 1990, ApJ, 348, 647
- Burleigh, M., Clarke, F., & Hodgkin, S. 2003, in White Dwarfs, ed. D. de Martino et al. (Dordrecht: Kluwer), 329
- Burleigh, M. R., Clarke, F. J., & Hodgkin, S. T. 2002, MNRAS, 331, L1
- Clarke, F. J., & Burleigh, M. R. 2004, in ASP Conf. Ser. 321, Extrasolar Planets: Today and Tomorrow, ed. J.-P. Beaulieu, A. Lecavelier des Etangs, & C. Terquem (San Francisco: ASP), 76
- Chauvin, G., Lagrange, A.-M., Dumas, C., Zuckerman, B., Mouillet, D., Song, I., Beuzit, J.-L., & Lowrance, P. 2005, A&A, 438, L25
- Dobbie, P. D., Burleigh, M. R., Levan, A. J., Barstow, M. A., Napiwotzki, R., Holberg, J. B., Hubeny, I., & Howell, S. B. 2005, MNRAS, 357, 1049 Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102
- Holberg, J. B., Oswalt, T. D., & Sion, E. M. 2002, ApJ, 571, 512
- Iben, I. Jr., & Livio, M. 1993, PASP, 105, 1373
- Kepler, S. O., et al. 1991, ApJ, 378, L45
- Kim, S.-H., & Martin, P. G. 1994, ApJ, 431, 783
- King, A. R., Beer, M. E., Rolfe, D. J., Schenker, K., & Skipp, J. M. 2005, MNRAS, 358, 1501

Kuchner, M. J., & Seager, S. 2005, ApJ, submitted (astro-ph/0504214)

inclination. Again, in the present Letter we have identified massive WDs as promising targets. While WD cooling also produces a period change, this change is expected to be monotonic, while the change caused by a planet is periodic.

Finally, Dobbie et al. (2005) have used a near-infrared spectroscopic analysis of eight white dwarfs in an attempt to search for low-mass companions. They were able to place upper limits on putative companions at substellar masses (~0.07 M_{\odot}). We have also examined the WDs with cool companions reported by Wachter et al. (2003), who used 2MASS photometry. However, none of the confirmed high-mass WDs appears to be on that list.

We should also note that the probability of even a Jovianmass planet (most likely of CO composition) at 0.01 AU eclipsing its host WD is rather small, $\sim 2\%$. Note, however, that a Jovian planet of CO composition will be larger (by more than a factor of 6) than a 1.2 M_{\odot} white dwarf (e.g., Zapolsky & Salpeter 1969), thus enabling it to produce a total eclipse.

If future observations fail to detect any disks or planets around massive WDs, this may mean that the formation of dust is somehow suppressed in these somewhat unusual, hydrogenpoor environments.

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REFERENCES

Liebert, J., Bergeron, P., & Holberg, J. B. 2005, ApJS, 156, 47

- Lin, D. N. C., & Papaloizou, J. C. B. 1985, in Protostars and Protoplanets II, ed. D. C. Black & M. S. Matthews (Tucson: Univ. Arizona Press), 981
- Livio, M., Pringle, J. E., & Saffer, R. A. 1992, MNRAS, 257, 15P
- Meyer, M. R., et al. 2004, ApJS, 154, 422
- Mochkovitch, R., & Livio, M. 1990, A&A, 236, 378
- Mullally, F., Mukadam, A., Winget, D. E., Nather, R. E., & Kepler, S. O. 2003, in White Dwarfs, ed. D. de Martino et al. (Dordrecht: Kluwer), 337 Nauenberg, M. 1972, ApJ, 175, 417
- Pringle, J. E. 1981, ARA&A, 19, 137
- 1991, MNRAS, 248, 754
- Schneider, G., Song, I., Farihi, J., Zuckerman, B., Becklin, E., Lowrance, P., Macintosh, B., & Bessell, M. 2005, in Poster Proceedings of A Decade of Extrasolar Planets around Normal Stars, ed. M. Livio (Baltimore: STScI), in press
- Stevens, I. R., Rees, M. J., & Podsiadlowski, P. 1992, MNRAS, 254, 19P
- Wachter, S., Hoard, D. W., Hansen, K. H., Wilcox, R. E., Taylor, H. M., & Finkelstein, S. L. 2003, ApJ, 586, 1356
- Walker, C. H., Wood, K., Lada, C. J., Robitaille, T., Bjorkman, J. E., & Whitney, B. 2004, MNRAS, 351, 607
- Wolszczan, A., & Frail, D. A. 1992, Nature, 355, 145
- Wood, K., Wolff, M. J., Bjorkman, J. E., & Whitney, B. 2002, ApJ, 564, 887
- Zapolsky, H. S., & Salpeter, E. E. 1969, ApJ, 158, 809