FINDING WHITE DWARFS WITH TRANSIT SEARCHES

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ABSTRACT

We make predictions for the rate of discovery of eclipsing white dwarf–main-sequence (WD-MS) binaries in terrestrial-planet transit searches, taking the planned Kepler and Eddington missions as examples. We use a population synthesis model to characterize the Galactic WD-MS population, and we find that, despite increased noise due to stellar variability compared with the typical planetary case, discovery of $\gtrsim 10^2$ nonaccreting, eclipsing WD-MS systems is likely using Kepler and Eddington, with periods of 2–20 days and transit amplitudes of $|\Delta m| \sim 10^{-4}$–$10^{-3}$ mag. Follow-up observations of these systems could accurately test the theoretical white dwarf mass–radius relation or theories of binary star evolution.

Subject headings: binaries: eclipsing — planetary systems — techniques: photometric — white dwarfs

1. INTRODUCTION

As white dwarf stars are comparable in size to the Earth, searches for terrestrial planets via transit of their parent stars should be capable of discovering white dwarf (WD) binaries as well. These can be distinguished from terrestrial planet systems because the WD will induce detectable Doppler shifts in the spectral lines of a main-sequence (MS) companion, whereas an Earth-like planet will not, due to its smaller mass.

An interesting coincidence is that the radius of a WD in a tight binary is comparable to its Einstein radius (Marsh 2001), which means that both gravitational lensing and eclipse may be important during transit. When combined with other information about the binary, observation of the change of magnitude during transit may allow measurement of the mass and radius of the WD, allowing a test of the relation originally predicted by Chandrasekhar (1935). Recent measurements of WD masses and radii using atmosphere models (Provencal et al. 1998) have modeling uncertainties that would be useful to test with another technique, and the range of WD masses available in binaries is larger than for single stars. The four known eclipsing WD–M-dwarf binaries are a good start (Marsh 2000), but a larger, alternatively selected sample could allow measurement of the variation of the relation with WD mass, age, or composition.

This paper addresses the question of how many white dwarf–main-sequence (WD-MS) binaries might be found in searches for transiting planets, with application to the Kepler¹ (Borucki et al. 1997) and Eddington² (Horne 2002) missions. We concern ourselves with WDs in detached binaries, since accreting WDs can be found by other means. In § 2, we discuss the various modes for discovery of WDs and the surveys that might detect them; then, in § 3, we describe the expected properties of WD-MS binaries in our Galaxy. In § 4, we estimate the number of binaries that might be found in the surveys mentioned above. In § 5, we discuss what one might do with any binaries discovered via this method, and in § 6, we conclude.

During the preparation of this paper, Sahu & Gilliland (2003) published a study of near-field WD microlensing for the Kepler mission. In their paper, numerical light curves for fiducial systems are presented, similar to the analytic light curves presented in Agol (2002); however, they did not attempt to accurately estimate the number of detectable systems, which is the goal of this paper.

2. WHITE DWARF BINARY VARIATIONS

First we consider the case in which the WD passes in front of the MS star (primary transit). The Einstein radius is $R_E = (4R_G a)^{1/2}$, where $R_G = GM/W^2$ is the gravitational radius for a lens of mass $M_W$, and $a$ is the semimajor axis of the binary. A WD in a binary system has a size, $R_{WD}$, which is comparable to the Einstein radius,

$$\frac{R_{WD}}{R_E} \approx 0.7 \left( \frac{M_W}{M_\odot} \right)^{-1/2} \left( \frac{a}{0.01 \text{ AU}} \right)^{-1/2} \left( \frac{R_W}{0.01 R_\odot} \right).$$

Thus, microlensed images (which will appear a distance $\sim R_E$ from the center of the WD) may be occulted by the WD so that we may have either dimming (favored if $R_{WD} > R_E$, i.e., small $M_W$ and $a$) or amplification (if $R_{WD} \ll R_E$, i.e., large $M_W$ and $a$).

If the occulting body (here the WD) is much smaller than the occulted body (MS star), the microlensing plus occultation equations take on an exceptionally simple form (Agol 2003), with the dimming or amplification dependent only on the surface brightness immediately behind the WD, so long as the WD is away from the edge of the MS star. The fractional change in flux during a transit is then given by

$$\Delta f_1 \equiv \left( \frac{2R_E^2 - R_{WD}^2}{R_{MS}^2} \right) \left( \frac{F_{MS}}{F_{MS} + F_{WD}} \right) \frac{I(r)}{I} \Theta(R_{MS} - r),$$

where $F_{MS}$ and $F_{WD}$ are the MS and WD fluxes, respectively, $R_{MS}$ is the radius of the MS star, $r$ is the projected distance of the WD from the center of the MS star, $I(r)/I$ is the limb-darkened intensity profile of the source normalized to the flux-weighted mean intensity, and $\Theta$ is the step function.

For close ($a \sim 0.1$ AU) WD-MS systems, $|\Delta f_1| \sim 10^{-4}$, since $R_{WD} \sim R_E \sim 10^{-2} R_{MS}$, similar to the transit depth of a terrestrial planet, though the effect will be a flux increase.
when $R_{\text{WD}}/R_{E} < 2^{-1/2}$. In a system of random inclination $i$ on the sky, the probability of transits along our line of sight is $\sim R_{\text{MS}}/a$, and for a small transiting body, the transit duration will be $T_{\text{tr}} \approx 2R_{\text{MS}} \sin i / v_{\text{orb}}$, where $R_{\text{MS}} \cos i$ and $v_{\text{orb}}$ is the relative orbital velocity.

The fractional change of flux when the MS star passes in front of the WD (secondary transit) is simply given by $\Delta f_{2} \equiv -F_{\text{WD}}/(F_{\text{WD}} + F_{\text{MS}}) < 0$. The transit will obviously be deeper for younger, more luminous WDs. The luminosity of a typical WD 1–10 Gyr after birth is on the order of $10^{-3}$ to $10^{-5} L_{\odot}$, so that terrestrial planet searches should be well suited to detecting these events too. Note that these will be flat-bottomed transits but will have the same durations and transit probabilities as the complementary primary transit. If the orbit is circular, as will be the case for close systems, a given light curve will exhibit either both primary and secondary transits (though the transit depths $\Delta f_{1}$ and $\Delta f_{2}$ may be very different) or no transits at all.

There are other types of variations in WD-MS light curves, including fluctuations as a result of tidal effects, both directly due to tidal distortion of the MS star and indirectly due to increased MS rotation rate and, hence, increased stellar variability, which is described in detail in § 4.1. In addition, we may see variations due to irradiation of the MS star by a hot WD in the very youngest WD systems, neglected here, or due to flickering if the WD is accreting at a low level from the MS stellar wind, also discussed in § 4.1.

Since the predicted transit amplitudes are of the same order of magnitude as those for terrestrial planet transits ($\Delta f \approx |\Delta m| \sim 10^{-4}$ mag), surveys designed to search for other stars ought to pick up WD-MS systems too. To illustrate this, we use as examples the Kepler (Borucki et al. 1997) and Eddington (Horne 2002) missions. These satellites will continuously monitor the brightness of many stars at high photometric precision to search for periodic dimming characteristic of a transiting planet.

Kepler will monitor $\sim 10^{4}$ dwarf stars with $9 < V < 14$ in a $10^6 \times 10^6$ field centered on Galactic coordinates $(l, b) = (69^\circ 6, 5^\circ 7)$, for at least 4 yr. The proposed Eddington design is for a smaller $3^\circ \times 3^\circ$ field with deeper magnitude limits ($11 < V < 18$) and a lifetime of 3 yr. In the absence of published coordinates for the Eddington field, we use here the same $(l, b)$ as Kepler. Kepler will have a broad bandpass, extending from $400$ to $850$ nm, while Eddington may have two-color information (Bordé et al. 2003). Kepler will read out fluxes every 15 minutes and will have a fiducial sensitivity (similar to that of Eddington) of $2 \times 10^{-5}$ for a 6.5 hr exposure of a $V = 12$ G2 V star.

3. WHITE DWARFS IN BINARIES

3.1. Evolution to the WD-MS Stage

The evolution of a zero-age main-sequence (ZAMS) binary system to a WD-MS system proceeds via one of two main pathways, according to whether or not Roche lobe overflow occurs en route, the critical initial orbital separation being at $a_{\text{crit}} \sim 10^{-2} - 10^{-1} R_{\odot}$; in both cases, the more massive star has evolved into a WD, while the other is still on the MS. The lifetime of this phase depends on the difference in main-sequence lifetimes of the two stars.

If the primary fills its Roche lobe on the red giant branch (RGB) or asymptotic giant branch (AGB), then the ensuing mass transfer will most likely be dynamically unstable, and a common envelope phase will result (Iben & Livio 1993), in which the envelope of the evolved star is heated by friction as the secondary and the core of the giant orbit inside it. This ends either when the stars coalesce or when the envelope is heated sufficiently that it escapes the system, leaving a WD-MS binary with greatly reduced orbital separation compared with the initial ZAMS system. The orbit will be circular, since tidal circularization will have occurred in any system in which a giant star is close to overflow.

If the orbital separation is sufficiently large that the primary does not overflow on the RGB or AGB, then it is affected only as the primary loses its envelope in the planetary nebula phase, leading to an increase in the orbital separation. We therefore expect that the Galactic WD-MS population will consist of two distinct groups of sources in $P$-space: the short-period systems from systems in which overflow has occurred and the long-period systems in which no Roche lobe has been filled.

3.2. Population Synthesis

A population synthesis approach was used to quantify the properties of the Galactic WD-MS population. Evol-

olutionary tracks were computed using the rapid-evolution BSE code (Hurley, Pols, & Tout 2000). Following the preferred model A of Hurley et al. (2000), we distribute the primary mass according to the initial mass function (IMF) of Kroupa, Tout, & Gilmore (1993), while the secondary mass distribution we choose to be flat in the mass ratio $q = M_{2}/M_{1}$, for $0 < q < 1$. The initial orbital semimajor axis distribution is flat in $\log a$. These initial conditions, along with, most notably, a constant star formation rate over the age of the Galaxy, a binary fraction of $100\%$, solar metallicity across all stars, a common envelope efficiency parameter $\alpha = 3.0$, and zero initial orbital eccentricity, were found by Hurley et al. (2000) to best reproduce the observed numbers of double-degenerate, symbiotic, cataclysmic variable, and other binary star populations in the Galaxy. Here we evolve pairs in which both stars have masses between $0.1$ and $20 M_{\odot}$, and the initial semimajor axis distribution extends from $2$ to $10^{5}$ ZAMS stellar diameters. Note that the BSE code uses the Nauenberg (1972) mass-radius relation for WDs.

We distribute this population according to a double exponential disk model, with scale length 2.75 kpc. The scale height ($h$) is chosen to vary according to stellar age ($t$), with $h \propto t^{1/2}$ set equal to 100 pc for stars born today and to 300 pc for the oldest stars in the disk. We use the extinction corrections of Bahcall & Soneira (1980) and thus model the stars in the Kepler field of view within the magnitude limits of the survey. We normalize to the number of dwarf stars counted in this field ($\sim 136,000$ with $9 < V < 14$, from the Kepler Web page: results can be rescaled if this number is later revised). We estimate that the total number of WD-MS systems within this sample of stars is $\sim 15,000$, while the Eddington sample should contain $\sim 35,000$ WD-MS systems. The resulting orbital period distribution of target WD-MS systems is plotted in
Figure 1 and displays the double-peaked structure expected from § 3.1, with a relative dearth of systems with periods from months to years. A similar distribution was predicted by de Kool & Ritter (1993).

4. DETECTING WHITE DWARFS

The detectability depends on the signal-to-noise ratio of all transits combined in the time series for a given system. We require that the transit duration be at least 1 hr (four Kepler time samples) for detection.

We assume that photon counting statistics typically dominate the noise but also add in a fractional instrumental noise of $10^{-5}$. For simplicity, we neglect limb darkening. Shorter period systems are doubly favored, since the time spent in transit and the probability of a transit in a system with random orientation both scale as $P^{-2/3}$. For this reason, Kepler's sensitivity—designed to detect the longer period terrestrial systems—is easily good enough to detect a large fraction of the transiting WD-MS systems within the magnitude limits at good signal-to-noise ratios. The same is not true of Eddington, with its deeper magnitude limits, which restrict most detectable transits to lower mass MS primaries. The properties of the detectable systems, assuming an 8 $\sigma$ detection threshold, and the parent population from which they are drawn are illustrated in Figures 1, 2, and 3 for Kepler. The total numbers of WD-MS systems detectable are summarized for both Kepler and Eddington in Table 1. We split the transits into the three modes of detection described in § 2. Note that many systems have both detectable primary and secondary transits. For a blind search, a number of transits ($\geq 3$) would need to be seen for detection as a periodic signal among the noise, but if radial velocity information were additionally available, it is possible that an identification could be made based on fewer transits. For this reason, systems at all periods are included as detectable (weighted by their transit probabilities and appropriate signal-to-noise ratios). If no such additional information is available, the curves in Figure 1 should be cut off at about $P \sim 1.3$ yr, though this makes little difference to the overall number of detectable systems, as a result of the underlying WD-MS period distribution.
Table 1 shows that several hundred transiting WD-MS systems are, in principle, detectable with each mission. However, the most serious (and least well-defined) limitation is still to be added: that of stellar variability noise, which is discussed in the following section.

4.1. Stellar Variability

The issue of stellar microvariability is of concern in terrestrial planet transit surveys (Jenkins 2002; Batalha et al. 2002; Aigrain et al. 2003). Variability levels are higher and, hence, more of a problem for WD-MS systems. This is because the majority of detectable systems (Fig. 1) have short orbital periods, $P \lesssim 30$ days, and at these short periods, tidal effects due to the WD are significant. (Note that the BSE code follows tidal effects in detail.) Synchronization of the MS star’s rotation with the orbital period is rapid if the MS star has a convective envelope ($M_{\text{MS}} \lesssim 1.6 M_\odot$) and $P \lesssim 10$ days. This is the case for about half of the transits detectable with Kepler (see Fig. 2) and most for Eddington. Rapidly rotating late-type stars display increased starspot activity (Messina, Rodonò, & Guinan 2001) and, hence, greater photometric variability due to these starspots rotating in and out of sight. Individual spots persist for only a few rotational cycles, meaning that, over time, the variability has a random nature. The amplitude of this variability scales with rotational period approximately as $\sigma \propto P_{\text{rot}}^{-1.5}$.

Examination of the power spectrum of solar irradiance variations (Fröhlich et al. 1997; Jenkins 2002) shows that this starspot noise is present up to frequencies $\sim 25/P_{\text{rot}} \odot$. Of most importance in transit detection is the stellar noise on the timescale of a transit, since one can, in principle, filter out variability on other timescales (Jenkins 2002; Aigrain et al. 2003). For WD-MS systems with $P \sim 1$–10 days, we have $T_{\text{rot}} \sim 1$–3 hr. If a WD transit has $P_{\text{rot}} \sim P_{\text{orb}} < 25 T_{\text{tr}}$, then the fractional star-spot noise will be $\sim 10^{-4}$ and will drown out almost all WD transit signals, even if there are many transits during the survey lifetime. Effectively, this places a lower limit on the orbital period of detectable systems (of around $P \sim 2$ days for typical systems). At frequencies $\gtrsim 25/P_{\text{rot}}$, the noise is governed by convective (super-) granulation, has an amplitude $\sim 5 \times 10^{-5}$ in the Sun on the appropriate transit timescale, and is probably unaffected by rotation rate. This noise will, however, reduce detectability of faint transits.

We approximate all convective stars as solar in these respects and in Table 1 show the sizable effects of adding this variability noise upon the detection rates for Kepler, again requiring $8 \sigma$ detections. The Eddington mission, which will observe in two colors, may be able to use the color signature of the stellar variability to enhance detection probabilities (Bordé et al. 2003), in which case, our predictions without stellar variability may be more appropriate.

More massive MS stars have radiative envelopes and smaller $|\Delta f|$ for transits since their radii are larger. For these stars, there is less detailed literature available on stellar microvariability, so we do not attempt to calculate its expected impact on the WD-MS detection rate. We do, however, note that these stars can be intrinsically quite variable. Since the radiative tide is weaker, systems are most likely asynchronous, but Zaqarashvili, Javakhishvili, & Belvedere (2002) suggest that, in this case, tides can excite the fundamental mode of pulsation of the star, potentially leading to oscillations on roughly the timescale of a transit. We note also that some observations (Dempsey et al. 1993) suggest that stars in close binaries display greater activity than single stars of the same rotation rate. Thus, the numbers of detectable systems given in Table 1 for MS primaries with radiative envelopes are likely to be reduced by variability, but we have not attempted to quantify this reduction. Extensive data on these topics may only be acquired once space-based transit searches fly.

An additional source of microvariability in the light curve may be from flickering as the WD accretes at a low level from the MS star’s wind. To have an accretion luminosity $L_{\text{WD}} \sim 10^{-4} L_\odot$, the WD needs to accrete at a rate $\sim 10^{-15} M_\odot \text{yr}^{-1}$ (cf. the solar mass-loss rate $\sim 10^{-14} M_\odot \text{yr}^{-1}$). Only a fraction of the mass lost from the MS star will be accreted by the WD, though we note that stellar wind mass loss may be enhanced in close binaries.

5. Discussion

As is evident in Figure 1, it is unlikely that WDs will provide a significant source of spurious Earth-like transits at $P \sim$ years, given the dearth of WD-MS systems and (hypothesized) large numbers of terrestrial planets at these periods. In addition, primary transits will be microlensing events at these times. Although WD companions are easily distinguished using radial velocity observations, it is useful to know that terrestrial planet signatures will not be swamped by those of WDs.

A large sample of close WD-MS systems would enable useful tests of binary star evolution theories (such as common envelope evolution). Also, if the mass and radius of the WD can be separately determined, then the WD mass-radius relation could be tested. The transiting WDs cannot, in general, be observed other than by their dimming effect upon the MS star, so that all properties must be inferred. This approach is, however, independent of WD atmosphere modeling.

The Kepler and Eddington missions easily have the sensitivity to produce high-quality light curves of short-period WD-MS systems since they are designed to search for longer periods. The Kepler mission is set to detect stars over a range of apparent magnitudes, while the Eddington mission is to detect stars over a range of apparent magnitudes.
period terrestrial planets. The inclusion of stellar variability may affect this somewhat. However, there is still a population of $\geq 50$ WD-MS systems detectable with each, given adequate signal processing power. Many of these systems display both detectable primary and secondary transits, which can be distinguished using their transit profiles. WD transits are longer in duration than, and shaped differently from, grazing MS-MS transits of the same depth. Radial velocity measurements should eliminate blending (dilution of a larger transit depth to the expected WD-MS level due to the presence of a brighter star within the same resolution element) as a source of confusion. This is simpler than in the planetary case, since WDs induce larger radial velocity variations on the orbital timescale. If variability or ellipsoidal modulation of the MS star flux, radial velocity variations, or characteristic accretion luminosity from the WD should draw attention to a system as a candidate close WD-MS system, then transit searches could also be targeted toward these sources since the geometric transit probability can be on the order of 10\% or more. Provided none of these is a significant noise source on the transit timescale, discovery of the transits in the light curve is possible and system parameters therefore extractable. Although it has been proposed that systems displaying large radial velocity variations be left out of the Kepler survey (D. Sasselov 2003, private communication), the findings of this paper strongly argue for the inclusion of candidate WD-MS systems in the target lists of transit surveys.

It has been noted by Gould, Pepper, & DePoy (2003) that the sensitivity of Kepler to habitable planets could be significantly increased by pushing the magnitude limit for red MS stars to \( V = 17 \). Such a change would also be expected to increase the survey’s sensitivity to WD-MS systems, since the typical orbital periods of transiting systems are shorter, and so the required signal-to-noise ratio is more easily achieved. In addition, we expect there to be a large underlying population of late MS star–WD systems available for detection. However, it should be noted that later-type stars tend to be more photometrically variable, which may complicate the situation.

We need eight quantities to fully characterize a given system: \( M_{\text{MS}}, R_{\text{MS}}, M_{\text{WD}}, R_{\text{WD}}, \pi, \) \( L_{\text{WD}}, \) and \( L_{\text{MS}} \). Orbits are expected to be circular. The effect of microlensing complicates the parameter extraction in some sense, since the primary transit depth depends on both WD mass and radius. We have a number of observables from the transit light curves: \( P, T_r, \) and the primary and secondary transit magnitude changes, \( \Delta m_1 \) and \( \Delta m_2 \). Ingress/egress times, which are in duration, will be unmeasurable if the proposed 15 minute exposures of Kepler are used. With radial velocity follow-up, we can also measure \( v_{\text{orb, MS}} \). More information is clearly necessary to solve for all system parameters. MS modeling can give us \( M_{\text{MS}}, R_{\text{MS}}, \) and \( L_{\text{MS}} \), at least in principle, though this may not be accurate for particularly active stars or those that have passed through common envelopes. If the distance to the system is known (e.g., from \textit{Space Interferometry Mission} parallax measurements), then the situation may be improved. If one is able to model the limb darkening of the MS star in the primary transit, then perhaps more information might be extracted. The potentially large numbers of such systems available in transit surveys make feasible statistical tests of WD and binary star theory.

6. CONCLUSIONS

Since the Kepler and Eddington missions are designed to detect terrestrial planets, they are ideal for detecting WDs as well. White dwarfs have more modes of detection than planets due to their larger masses (and luminosities), but their detection is complicated by the (tidal) effects of these larger masses. In principle, at least 50 new WD-MS systems might be unambiguously detected with either mission, while, at most, 500 could be detected if stellar variability were less significant than our estimates. Follow-up observations of the systems might yield mass and radius estimates for the (unseen except by transit) WDs and, hence, give a test of the WD mass-radius relation or of theories of binary star evolution.

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