A SEARCH FOR ASTEROIDS, MOONS, AND RINGS ORBITING WHITE DWARFS

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ABSTRACT

Do white dwarfs host asteroid systems? Although several lines of argument suggest that white dwarfs may be orbited by large populations of asteroids, transits would provide the most direct evidence. We demonstrate that the Kepler mission has the capability to detect transits of white dwarfs by asteroids. Because white-dwarf asteroid systems, if they exist, are likely to contain many asteroids orbiting in a spatially extended distribution, discoveries of asteroid transits can be made by monitoring only a small number of white dwarfs, compatible with Kepler’s primary mission, which is to monitor stars with potentially habitable planets. Possible future missions that survey 10 times as many stars with similar sensitivity and minute-cadence monitoring can establish the characteristics of asteroid systems around white dwarfs, such as the distribution of asteroid sizes and semimajor axes. Transits by planets would be more dramatic, but the probability that they will occur is lower. Ensembles of planetary moons and/or the presence of rings around planets can also produce transits detectable by Kepler. The presence of moons and rings can significantly increase the probability that Kepler will discover planets orbiting white dwarfs, even while monitoring only a small number of them.

Key words: minor planets, asteroids: general – planetary systems – white dwarfs

1. INTRODUCTION

Stars are orbited by dust, asteroids, planets, and their moons. As each star evolves, its planetary system evolves as well, through a combination of stellar expansion, mass loss, and dynamical interactions. In spite of the fact that the first planet to be discovered orbits a pulsar (Wolszczan & Frail 1992), we still know little about the planetary systems around stellar remnants. Fortunately, a variety of methods are poised to change this. Pulsar timing studies in combination with Hubble Space Telescope (HST) images have found a planet in a circumbinary orbit around a binary consisting of a millisecond pulsar and a white dwarf (Sigurdsson et al. 2003). Timing measurements of pulsating compact stars can also identify candidate planetary systems around highly evolved stars (i.e., Silvotti et al. 2007), with complementary Spitzer observations able to detect or place limits on possible planetary companions of white dwarfs (Mullally et al. 2009). In this paper, we point out that the Kepler mission has the sensitivity and cadence needed to detect transits of white dwarfs by asteroids.

1.1. Motivation

Calculations show that asteroid or cometary systems can survive stellar evolution (Alcock et al. 1986). While asymmetries in the mass loss can influence survivability, some white dwarfs could experience asteroid impacts at a rate of \(10^{-4}\) yr\(^{-1}\) (Parriott & Alcock 1998). Several independent lines of evidence suggest that some white dwarf stars do host circumstellar material ranging from dust to asteroids and planets (Howell et al. 2008; Jura 2008 and references therein; Farhi et al. 2009; Jura et al. 2009a, 2009b). Asteroid-sized objects, with diameters ranging from several tens of kilometers up to and including dwarf planets, are the primary focus of this paper. Their instantaneous orbital distance from the white dwarf ranges from the tidal limit out to the equivalent of the Sun’s Oort Cloud. We will also consider the possible effects of rings and moons orbiting planets in white dwarf systems.

White dwarfs with infrared excesses have been studied by a number of groups. A common conclusion is that circumstellar dust is present. These white dwarfs tend to exhibit unusually strong metal lines in their photospheres (von Hippel et al. 2007), perhaps showing the signs of enrichment by recent accretion of material from an asteroid. Indirect evidence of planetary material around warmer white dwarfs includes several stars that show metal lines in their photospheric spectrum (Zuckerman et al. 2007, and references therein). In white dwarfs, metals sink below the photospheres on extremely short timescales (of order days), so the presence of elements such as calcium argues that the stars have recently accreted metal-rich material.

As an example of possible asteroidal material surrounding a white dwarf, consider the recent work by Gansicke et al. (2007). They report observations of CaT and FeT double-peaked emission lines, interpreted to be from a circumstellar, metal-rich gaseous disk. The white dwarf itself is hot enough (\(T_{\text{eff}} \sim 22,000\) K) to burn off dust from the disk, accounting for the lack of an infrared excess. The disk itself is the likely remnant of a tidally disrupted rocky body of asteroid-sized mass (Gansicke et al. 2007). The case for a metal-rich disk is strengthened by observations of MgT absorption lines in the stellar spectrum. Dynamical modeling of the system by Gansicke et al. (2007) constrain the outer edge of the disk to be at about 1.2 \(R_\odot\), and places the inner edge at approximately 0.64 \(R_\odot\).

Zuckerman et al. (2007) provide an analysis of the white dwarf GD 362, including an estimate of the abundance of 17 elements accreted by that star. They conclude that an asteroid-mass object (either a remnant asteroid or the residual of a disrupted terrestrial planet) is needed to explain the abundance pattern. A very rough estimate of the size of an object needed to account for the metals seen in that star (10^{23} g) is of order...
80 km; such an object would produce a transit with a depth of 0.01%, or 100 ppm.

1.2. Goals

For every asteroid that is tidally disrupted, there must be many more with perihelia located much farther from the white dwarf. Direct detection of these asteroids is challenging. They have very little gravitational influence on their star and cannot presently be detected through either Doppler or ground-based photometric transit methods. Transits of white dwarfs by large asteroids can, however, be detected by Kepler, a space mission designed to detect the transits of Sun-like stars by Earth-like planets. Consider a white dwarf with a radius of 8000 km. An asteroid with a radius of 100 km (1000 km) will produce a fractional decrease in the amount of light received of 150 ppm (15,000 ppm), within Kepler’s detection limit. Many such asteroids of this size are known in our own solar system (an estimated 80,000 in the Kuiper Belt alone; Trujillo et al. 2001), so it is reasonable to expect that they exist elsewhere as well.

In Section 2, we show that the Kepler observatory can discover asteroids orbiting white dwarfs by identifying short-lived downward deviations from the baseline flux in white dwarfs associated with transits by asteroids. In Section 3, we discuss what we can learn through Kepler monitoring of a small set of white dwarfs. Asteroid transits or significant limits on white dwarf asteroid systems are a certain science return. In addition, depending on the structure of white dwarf planetary systems, transits by rings and/or moons may also be detected by monitoring a modest number of white dwarfs.

2. Kepler Detections of Asteroid Transits

2.1. Detection of Transits

The depth of a transit and its time duration determine its level of detectability. If \( A_{\text{ast}} \) is the projected area of the asteroid, and \( A_{\text{wd}} = \pi R_{\text{wd}}^2 \) the cross-sectional area of the white dwarf, the depth of the transit is \( \frac{A_{\text{ast}}}{A_{\text{wd}}} \). The calculations for asteroids transiting white dwarfs mirror the results for an Earth-like planet transiting a Sun-like star, because the relative size scales are similar. For an asteroid of a given size, the depth is greatest for more massive white dwarfs, which are smaller.

Asteroid transits against a white dwarf will be of short duration and may have distinctive profiles. The time required for the asteroid’s center of mass to cross the diameter of the white dwarf is \( \tau_{\text{cross}} = 2 \frac{R_{\text{wd}}}{v} \), where \( v \) is approximately equal to the orbital velocity,

\[
\tau_{\text{cross}} = 9.4 \text{ minutes} \left( \frac{R_{\text{wd}}}{7.5 \times 10^8 \text{ cm}} \right) \left( \frac{a}{1 \text{ AU}} \right)^{\frac{1}{2}} \left( \frac{0.8 \ M_{\odot}}{M_{\text{wd}}} \right)^{\frac{1}{2}}.
\]

Because the orbital speed, \( v \), decreases with increasing \( a \), an asteroid of fixed size produces a longer event when it is farther from the white dwarf. The crossing time is larger for less massive white dwarfs because the orbital speed is smaller (for a given \( a \)) and because the radius of a low-mass white dwarf is larger. The ingress and egress may be distinctive because many asteroids will not be massive enough to have been pulled into a spherical shape by self-gravity.

We have carried out a set of calculations to determine how large an asteroid must be in order for its transit against a white dwarf of given brightness to be detectable by Kepler. We use the information on the Kepler Web pages to estimate the number of detected photoelectrons per minute: \( N = 1.3 \times 10^7 \left(10^{-0.4(M_{\text{KEPLER}}-12)} \right) \) per minute. For representative examples, we used three Kepler magnitudes of \( M_{\text{KEPLER}} = 12.2, 14.8, 15.8 \). The latter two represent white dwarfs that are within the Kepler field, while the brighter example is to illustrate the case of a favorable (but more hypothetical) target. For each candidate white dwarf we carried out two sets of calculations. In the first set, we assumed that the mass of the white dwarf was \( M_{\text{wd}} = 0.8 \ M_{\odot} \) and used the corresponding radius. In the second set, we used \( M_{\text{wd}} = 1.3 \ M_{\odot} \) and decreased the value of \( R_{\text{wd}} \) accordingly. Then, for each of 60 values of the orbital separation \( a \), we computed the diameter of an asteroid for which we would have a 1\( \sigma \), 2\( \sigma \), and 3\( \sigma \) detection of the transit, by integrating over the crossing time. The results are shown in Figure 1. For lower-mass white dwarfs, asteroids of smaller diameter can produce detectable transits. For the brightest white dwarf, transits of asteroids in the 100 km class can be detected even when they are relatively close to the white dwarf. The dimmer the white dwarf, the farther from it must a 100 km asteroid be in order for its transit to be detected by Kepler. In the solar system, the Kuiper Belt extends from roughly 30 AU to 50 AU. Large interlopers from the Oort Cloud, such as 2006 SQ372, are also found in this region, while the bulk of the Oort cloud lies beyond 1000 AU. Although the white dwarf systems we target for Kepler study may be very different, the example of the solar system indicates that it is good to be sensitive to asteroids at large values of \( a \).

2.2. The Numbers of Asteroids

The probability of detecting a transit by an individual asteroid is small, because it is proportional to the maximum angle of orbital inclination for which a transit can be observed: \( \frac{R_{\text{wd}} + R_{\text{ast}}}{a} \), where \( R_{\text{wd}} \) is the radius of the white dwarf, \( R_{\text{ast}} \) is the radius of the asteroid, and \( a \) is the orbital separation. If a typical value of \( \frac{R_{\text{wd}} + R_{\text{ast}}}{a} \) is \( 8 \times 10^8 \) cm, and the average value of \( a \) at the time of transit is 1 AU, then taking inclination alone into account, we would have to observe almost 30,000 white dwarfs to have a good chance of detection.\(^5\) If each white dwarf is orbited by many asteroids, the probability of detection increases. Should all of the asteroids orbit in a common plane, however, we must still monitor a large number of white dwarfs to have a good chance of detection.

Fortunately, our own solar system offers hope, and star and planet formation theory also suggest that planetary systems each host large numbers of asteroids and that the orbits are not aligned. The Oort Cloud (\( a > 1000 \) AU), which may have as much as 100 Earth masses (Marochnik et al. 1988) is expected to have a nearly spherical distribution. Some of its members have perihelia within the Kuiper Belt (30–50 AU), while others could make even closer approaches. If each white dwarf we observe has a distribution of asteroids with the geometry of the Oort Cloud, we have a good chance to detect transits with Kepler monitoring of even a single white dwarf. The Kuiper Belt itself has a scattered component in which the average orbital inclination angle, \( i \), is 12\(^\circ\), while individual orbits can be even more inclined (see Sheppard 2006, and references therein). Therefore, if the asteroid systems of white dwarfs have

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\(^5\) Equation (1) neglects the size of the asteroid, the proper motion of the white dwarf, and assumes that the transit occurs along a diameter of the disk.

\(^6\) In this discussion of orientation effects we neglect duty cycle issues, but note that if the orbital period is large compared to the total time during which observations occur, there is a further diminution of the detection probability.
a geometry similar to that of the scattered Kuiper Belt, and if we could monitor 10–15 white dwarfs, we would have a good chance that the equivalent of the scattered “Kuiper” Belt of one or more of them was inclined toward our line of sight.

Assuming a spherical distribution, we can quantify the probability of detecting a transit as a function of $a$ as follows. We compute the number of asteroids that would have to have periastra at a particular value of $a$ in order to have a probability near unity of detecting the transit. Given $(R_{wd} + R_{ast}) = 8 \times 10^8$ cm, then for $a = (0.1, 1, 10, 100)$ AU, the number of such asteroids is $(1.9 \times 10^5, 1.9 \times 10^4, 1.9 \times 10^3, 1.9 \times 10^2)$. These numbers assume that the interval $T$ during which continuous observations occur spans the orbital periods of the asteroids. In fact, $T$ will be longer than $P_{orb}$ for small orbital apastra, and the scaling above holds for those separations. Even better, for $T > n P_{orb}$, $n$ transits will be detected; confidence that the photometric dips were caused by transits can therefore be high, just as multiple planetary transits enhance confidence in the discovery of planets. For wider separations, however, the probability is reduced by a factor of $T/P_{orb}$. For circular orbits, the number of asteroids needed to have a transit detection probability near unity is

$$N = 1.8 \times 10^4 \left( \frac{F_T}{T} \right) \left( \frac{M_\odot}{M} \right) \left( \frac{R_{wd} + R_{ast}}{8 \times 10^8 \text{ cm}} \right) \left( \frac{a}{\text{AU}} \right)^2. \quad (2)$$

If $T = P_{orb}$ for $a = 1$ AU, then the numbers of asteroids needed to ensure detection for $a = (0.1, 1, 10, 100)$ AU are $(1.9 \times 10^5, 1.9 \times 10^4, 6.0 \times 10^3, 1.9 \times 10^2)$.

These numbers are modest enough to suggest that, unless the white dwarf systems are depleted in 100 km class asteroids relative to the solar system, Kepler can discover asteroid transits by monitoring a handful of white dwarfs. Furthermore, these numbers above are small enough that a null result would represent a meaningful limit.

### Figure 1

Asteroid diameter (in km) necessary in order to detect a transit vs. the orbital separation (in AU) at the time of transit. The significance of the detection was estimated by integrating over the crossing time. The mass of the white dwarf was taken to be 0.8 $M_\odot$ in the solid curves and 1.3 $M_\odot$ in the dashed curves. For each white dwarf, the (lowest, middle, and top) curve corresponds, respectively, to a $\sigma$, $2\sigma$, and $3\sigma$ detection. The two right panels refer to the Kepler magnitude of specific candidate white dwarfs known to be in the Kepler field.

### 2.3. Interpretation: Individual Events

The characteristics of transit light curves are related to the properties of the asteroid.\(^7\) If the ingress and egress can be resolved in time, there will be an interval $\delta t_{in}$ during which the flux declines by $\Delta F$, a second interval $\Delta T$, during which the flux remains at its steady minimum value $F - \Delta F$, and a third interval $\delta t_{out}$ during which the transit ends and the flux returns to the level, $F$ it would have had without the transit.

It is important to note that, particularly for the bright white dwarfs likely to be monitored by Kepler, the white dwarf’s radius and mass can be estimated to high accuracy using good quality optical spectra and model fits to $T_{eff}$ and $\log(g)$. The depth of the transit (the maximum downward deviation, $\Delta F$), therefore measures the projected area of the asteroid. The value of $\Delta T$, combined with the estimated white dwarf’s radius, provides an estimate of the asteroid’s speed, hence its distance from the white dwarf. If $\delta t_{in}$ and $\delta t_{out}$ cannot be measured, then we can use the time resolution of the observations to place upper limits on the linear dimensions of the asteroid. If they can be measured, then we can (1) determine the projected linear size of the asteroid at the time of ingress and (2) also at the time of egress. If they are different, then the asteroid may have been spinning; we can (3) check for consistency to determine if a realistic spin period is consistent with the observed change. If they are the same, we can (4) determine if the shape of the light curve is consistent with a disk-like structure. Using the area (from the depth of the transit) to estimate the possible mass, we can (5) check if we expect the asteroid to be spheroidal. Finally, we can (6) check if the linear dimensions as estimated during ingress and egress are consistent with the projected area, as estimated from the depth of transit.

\(^7\) Note that the white dwarf may be intrinsically variable. If the variability is periodic, it will not interfere with our ability to detect a transit. Nevertheless, when analyzing the light curves, care must be taken to consider the influence of any intrinsic variability because if the variability is complex, detectability may require a deeper, longer-lasting transit. To simplify in the text, we discuss the flux $F$ as if it is constant when a transit is not occurring.
Note that if an event fails consistency checks, we can rule it out as a transit candidate. Passing the checks does not however confirm the transit interpretation. When transit candidates are identified, an exhaustive analysis is required of any effects that could have produced a false positive signal. In an individual case, if the asteroid orbit happens to not be highly eccentric and if $a$ is not much larger than an AU, we may see a repeat during the lifetime of Kepler: this will confirm the transit model. Overall, it is likely that an asteroid population large enough to produce a transit by one asteroid will produce transits by several independent asteroids, and that a set of self-consistent results will increase confidence in the transit interpretation.

2.4. Interpretation: Populations of Asteroids

The nature of the results that can be obtained by Kepler depends on the characteristics of planetary systems. Because the progenitor of a white dwarf was a giant, it seems likely that the region within roughly an AU was cleared of planets and asteroids. Yet, the evidence cited in the introduction of this paper indicates that asteroids can and do approach close to white dwarfs.

If the monitored white dwarfs have close-in asteroids with small semimajor axes, we will discover “repeats” in a sense: multiple transits with similar characteristics. If the monitored white dwarfs have large asteroids, the photometric dips during transits will be highly significant. If the monitored white dwarfs have $\sim 10^{12}$ asteroids in a Kuiper-like belt, several events caused by different asteroids will be observed. Even if individual events are detected with low confidence (e.g., $1 - \sigma$ photometric dips), we may be able to derive significant results when several such events are detected. This is because the probability of detecting multiple dips due to random processes (which we can assess through observations of other stars) is expected to be low. Thus, multiple transits caused by one or by several asteroids, or deep transits, or long-lasting transits would provide information about some characteristics of the asteroid system.

It is certainly possible, however, that for one or more white dwarfs, no highly significant events are discovered. In this case, given the estimated efficiency, which will be well known based on Kepler’s observations of hundreds of thousands of other stars, we can place quantitative limits on the presence of close-in, and/or large, and/or numerous asteroids around any given white dwarf. We therefore expect monitoring of each white dwarf to produce significant results of either a positive or a negative nature.

3. PROSPECTS

3.1. Asteroids

The Kepler team is about to announce the first year’s results. The mission is scheduled to take data for 3.5 years, and could extend operations for a total duration of 5 years. Kepler can transmit data on approximately 170,000 targets, most main-sequence stars which are being monitored in hope of detecting transits by Earth-like planets. A limited number of data slots are available to monitor other targets suggested by the community. Two modes of monitoring are available: 30 minute cadence and 1 minute cadence. Equation (1) shows that the 1 minute mode is needed to detect transits by close-in asteroids. Although asteroids making close approaches to the white dwarf must be larger if their transits are to be detectable, it is important to be sensitive to close approaches for two reasons. First, the probability that the orientation is favorable scales as $1/a$. Second, if the orbit is circular, the transits could be periodic, allowing for repeated transit observations. One-minute cadence is also important if we are to resolve the transit light curve for more distant approaches.

The need for 1 minute cadence limits the number of white dwarfs that can be monitored. In addition, only a small number of bright white dwarfs in the Kepler field are known. Fortunately, the large numbers of asteroids expected per white dwarf will almost certainly make it possible to discover asteroids by monitoring almost any white dwarf that has them.

Because planets are likely to form in a bottom-up approach, stellar formation seems likely to always produce small masses that will be gravitationally bound to the star, regardless of whether large planets form. Even though stellar evolution is associated with mass loss from the system, a large number of asteroids should remain bound. In addition, the dynamical evolution of planetary orbits during stellar evolution seems likely to yield collisions and additional space debris in the form of asteroids. This line of argument is consistent with the data summarized in the introduction, which argues independently that asteroids orbit white dwarfs. Nevertheless, some white dwarfs may be less likely to host asteroid systems, at least the ones associated with planet formation. Consider, for example, a white dwarf that emerged from a common envelope episode. This suggests that the white dwarfs most suitable for the first monitoring program are those with masses near or above $0.6 M_\odot$; in addition, they should not have close stellar companions.

If white-dwarf asteroid systems occupy a region similar to the solar system’s scattered disk, then by monitoring a set of white dwarfs, we can sample a random distribution of possible orientations. If therefore, Kepler can monitor (for approximately one year each) roughly a dozen bright white dwarfs, it should discover asteroids and begin to quantify the fraction of white dwarfs with asteroids in the 100 km class.

Future projects that can take this study further are under consideration. Since missions with Kepler’s sensitivity can detect asteroids around white dwarfs, a more comprehensive all-sky survey monitoring $\sim 2.5 \times 10^6$ stars (such as that proposed for the Transiting Exoplanet Survey Satellite) will be able to establish the statistics of asteroid systems around white dwarfs: the frequency as a function of white dwarf properties, and the distributions of asteroid sizes and orbital separations.

3.2. Planets, Moons, and Rings

White dwarfs may well be orbited by planets, but the probability $P$ that the orientation of a planetary orbit is favorable for the detection of a transit is small,

$$P = \frac{(R_{wd} + R_{pl})}{a} = 2.0 \times 10^{-4} \left( \frac{R_{wd} + R_{pl}}{3 \times 10^8 \text{ cm}} \right) \left( \frac{\text{AU}}{a} \right). \quad (3)$$

This implies that thousands of white dwarfs would have to be monitored in order to detect transits by planets, which is not compatible with the primary goal of the Kepler mission. Nevertheless, other signatures of planets are more likely to be detected by Kepler.

Although planetary rings are generally composed of bits of debris that are individually too small to produce detectable transits, the combined effect can be to absorb and scatter enough

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5 White dwarfs in close binaries and those that have been involved in prior mass transfer may also be interesting, but the science to be explored in those cases is different. We therefore suggest that a limited program focuses on isolated white dwarfs.
light that the transit of the ring will be detectable (e.g., Ohta et al. 2009 and references therein). In this case, the ingress and egress profiles are likely to be symmetric and distinguishable from the patterns produced by an isolated mass. Strategies for searching for evidence of rings and moons in transit light curves have been developed (Barnes & Fortney 2004; Barnes 2004). HST observations of the planetary transit of HD 189733 were able to derive a convincing null result, ruling out the presence of rings or moons around HD 189733b through a detailed light curve analysis (Pont et al. 2007). Kepler could do the same, or else discover moons and rings around white dwarf planets, should they exist.

To compute the probability of detecting a transit by a ring, the term \( R_{pl} \) in Equation (2) must be replaced by \( R_{ring} \sin(\theta) \). This expression \( R_{ring} \) is the outer diameter of the ring system and can be significantly larger than \( R_{pl} \). Thus, even though the planet itself may be out of our line of sight, the ring could transit. In the case of Saturn, for example, the outer radius of its ring system \( (4.8 \times 10^{10} \text{ cm for the E ring}) \) is almost 10 times larger than the radius of the planet. The angle \( \theta \) in Equation (2) is the angle between the plane of the ring and the orbital plane of the planet. If \( \theta = 0 \), then transits by the ring will only be detected in some cases in which the planet transits as well. In those cases, the effect of the ring will be striking, because it will produce a diminuation in light from the white dwarf that lasts significantly longer than the transit by the planet. If, however, the plane of the ring is oriented at a non-zero angle \( \theta \) relative to the orbital plane, then the probability of a transit by the rings can be greater than the probability of a transit by the planet, \((R_{ring} \sin(\theta)) > (R_{pl} + R_{pl})\). If a Saturn-like planet were to orbit a white dwarf at \( a = 0.1 \text{ AU} \), then with \( \theta = 90^\circ \), the value of \( \mathcal{P} \) would be 0.04. If such systems are common, then a ring transit could be discovered by monitoring 1–2 dozen white dwarfs.

Planets are also orbited by moons. Our own solar system contains more than 150 moons, many large enough to produce transits of a white dwarf that would be detectable by Kepler. The cases in which a moon is likely to produce a transit, even if the planet does not transit, are those in which the planet orbits the star many times during the course of the monitoring observations and in which the moon also orbits the planet many times during the same interval. Let \( \Delta a_{pl} \) be the distance between the planet and its moon, and let \( \theta \) be the angle between the orbital planes of the moon and the planet. To compute \( \mathcal{P} \), the term \( R_{pl} \) in Equation (2) must be replaced by \( a_{pl} \sin(\theta) \). Consider a Saturn-like planet orbited by a moon at \( 10^{11} \text{ cm} \) (an 11 day orbit). If the distance of the Saturn-like planet from a 0.8 \( M_\odot \) white dwarf is equal to 0.2 \( \text{ AU} \) (a 36.5 day orbital period), and \( \theta = 90^\circ \), then \( \mathcal{P} = 0.04 \). As with the case of rings, the probability of that a detectable transit will occur during a year of monitoring 1–2 dozen white dwarfs is significant.

Although we do not have the a priori knowledge needed to assess the likelihood of transits by rings or moons, the discovery that exoplanets commonly have properties that were unexpected leads us to consider a range of possibilities for planets orbiting white dwarfs. The considerations above show that, if white dwarfs tend to be orbited by close-in planets, and if these planets have rings and/or moons, there is a chance that Kepler will discover them by monitoring a modest number of white dwarfs. An all-sky survey with the sensitivity of Kepler would either discover such systems or definitively rule them out.

Consider the possibility that white dwarfs host both asteroid systems and close-in planets with rings and/or moons. Dynamical stability arguments place constraints on the number of close-in planets and on the linear dimensions of the system of moons orbiting each. Unless, therefore, the asteroid systems are deficient in large asteroids relative to what we might expect based on the solar system, transits by asteroids should provide the dominant signal.

### 3.3. Other White Dwarf Science

The continuous monitoring of white dwarfs can lead to significant scientific results in addition to those associated with asteroids. If coherent oscillations are present in these stars, astroseismic analysis would reveal these modes at amplitudes of 16 ppm (3\( \sigma \)) in just 1 month of data on a 15th magnitude star, and 4.6 ppm (3\( \sigma \)) in one year. These are 10–30 times (or more) lower than any ground-based photometry has achieved. At these low levels new pulsating classes could well be discovered.

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