

Habitable Planets Around White Dwarfs: an Alternate Mission for the Kepler Spacecraft

Mukremin Kilic^{1,6}, Eric Agol², Abraham Loeb³, Dan Maoz⁴, Jeffrey A. Munn⁵,
Alexandros Gianninas¹, Paul Canton¹, Sara D. Barber¹

ABSTRACT

A large fraction of white dwarfs (WDs) may host planets in their habitable zones. These planets may provide our best chance to detect bio-markers on a transiting exoplanet, thanks to the diminished contrast ratio between the Earth-sized WD and its Earth-sized planets. The James Webb Space Telescope is capable of obtaining the first spectroscopic measurements of such planets, yet there are no known planets around WDs. Here we propose to take advantage of the unique capability of the Kepler spacecraft in the 2-Wheels mode to perform a transit survey that is capable of identifying the first planets in the habitable zone ($P = 4\text{-}30$ h) of a WD. We propose to obtain Kepler time-series photometry of 10^4 WDs in the Sloan Digital Sky Survey imaging area to search for planets in the habitable zone. Thanks to the large field of view of Kepler, for the first time in history, a large number of WDs can be observed at the same time, which is essential for discovering transits. Our proposed survey requires a total of 200 days of observing time, and will find up to 100 planets in the WD habitable zone. This survey will maintain Kepler's spirit of searching for habitable Earths, but near new hosts. With few-day observations and minute-cadences per field, it will also open up a completely unexplored discovery space. In addition to planets, this survey is sensitive to pulsating WDs, as well as eclipsing short period stellar and sub-stellar companions. These have important implications for constraining the double WD merger rate and their contribution to Type Ia supernovae and the gravitational wave foreground. Given the relatively low number density of our targets, this program can be combined with other projects that would benefit from high cadence and 'many-fields' observations with Kepler, e.g. a transit survey of a magnitude-limited, complete sample of nearby M dwarfs or asteroseismology of variable stars (e.g. RR Lyrae) in the same fields.

¹Department of Physics and Astronomy, University of Oklahoma, 440 W. Brooks St., Norman, OK, 73019

²Department of Astronomy, Box 351580, University of Washington, Seattle, WA 98195

³Institute for Theory and Computation, Harvard University, Cambridge, MA 02138

⁴School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel

⁵US Naval Observatory, P.O. Box 1149, Flagstaff, AZ 86002

⁶kilic@ou.edu

1. Background

Transiting exoplanets provide invaluable information on planetary physics, their formation, and evolution. The search for planets in the habitable zone has so far focused on solar-type stars and M dwarfs. However, transiting planets in the habitable zone around white dwarfs (WDs) may be common and they may provide our best chance to detect biomarkers on an exoplanet in the near future (Loeb & Maoz 2013).

WDs are as common as Sun-like stars, and they provide an energy source for planets for billions of years. Typical WDs have $M = 0.6M_{\odot}$, $R = 0.01R_{\odot}$, and $L = 10^{-4}L_{\odot}$, so a planet must orbit at ~ 0.01 AU to be at a temperature for liquid water to exist on its surface. The habitable zone around WDs extends from 0.005 AU ($P = 4$ h) to 0.02 AU ($P = 30$ h, Agol 2011; Monteiro 2010) for WDs older than about 1 Gyr. Figure 1 shows the evolution of the habitable zone around WDs (WDHZ) with time. A planet enters at the bottom of Figure 1 and moves vertically up the figure as its WD host ages, so it starts off too hot for liquid water, passes through the WDHZ, and then becomes too cold. The duration a planet spends within the WDHZ has a maximum of 8 Gyr at 0.01 AU; WDs have long-lived habitable zones.

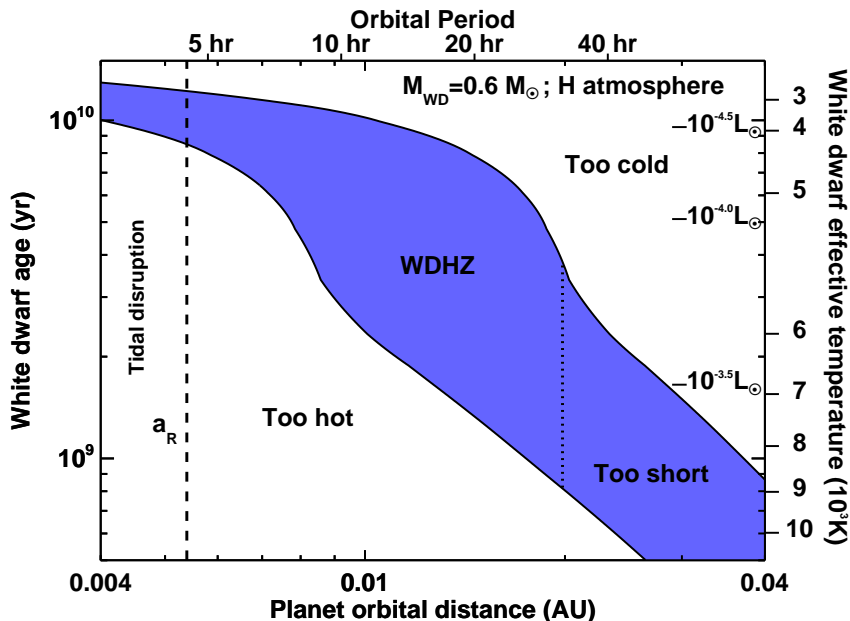


Fig. 1.— The habitable zone (shaded region) around $0.6 M_{\odot}$ WDs versus age and planet orbital distance (from Agol 2011). Dashed line (0.005 AU) is the Roche limit for Earth-density planets. Planets within 0.02 AU would be in the habitable zone for >3 Gyr.

We expect the planets within 1 AU of solar type stars to be destroyed in the giant phase (Villaver & Livio 2007, but see Silvotti et al. 2007). Hence, planets in the habitable zone around WDs must arrive there after this phase. Debes & Sigurdsson (2002), Livio et al. (2005), Faedi et

al. (2011), and Veras et al. (2013) describe several ways to form such planets near the WD or bring them closer. Planets can form out of gas near the WD, via the interaction or merger of binary stars (Kratzer & Perets 2012), or by capture or migration from larger distances. Planets have been detected around evolved, post-main-sequence stars, including millisecond pulsars and pulsar + WD systems (Wolszczan & Frail 1992; Sigurdsson et al. 2003; Beuermann et al. 2012). Wu & Lithwick (2011) have a dynamical instability model that can produce short period planets on Gyr timescales; the same mechanism is likely at work after the giant phases and could populate the habitable zone around WDs. The discovery of close-in planets around the post-main-sequence stars KIC 05807616 and V391 Pegasi demonstrate that such planets should also exist around WDs (Charpinet et al. 2011; Silvotti et al. 2007; Passy et al. 2012). Barnes & Heller (2013) and Nordhaus & Spiegel (2013) have emphasized that the tidal heating of a planet, until it achieves full circularization, in the WDHZ would lead to the loss of water. However, the young Earth was also a hot and dry place, but volatiles and water were then delivered to it by a large number of comets. It is likely that the process that populates the WD habitable zone could also lead to a heavy bombardment phase that could deliver water and volatiles to these planets (Loeb & Maoz 2013).

About 30% of the WDs in the solar neighborhood have metal-polluted atmospheres (Zuckerman et al. 2010). The source of metals is not accretion from the interstellar medium (Kilic & Redfield 2007). In addition, $\geq 4.3\%$ of WDs host debris disks (Barber et al. 2012), which are the remnants of tidally destroyed asteroids and planets (e.g., Klein et al. 2011). Hence, there is direct evidence from these debris disks that the interactions between giant planets can send asteroids, moons, or small (Earth-like) planets closer to the WD (Jura 2003; Veras et al. 2013). Therefore, short-period planets around WDs likely exist; but we have never looked at enough WDs to find them.

WDs are about the same size as Earth. Hence, earth-size (and even smaller) planets can easily be detected through photometric observations (Di Stefano et al. 2010; Faedi et al. 2011; Drake et al. 2010). Figure 2 shows model light-curves of a $0.6 M_{\odot}$ WD as it is eclipsed by a planet with $M = 1M_{\oplus}$ and another with $M = 10M_{\oplus}$ orbiting in the habitable zone of the WD. In the case of the $1 M_{\oplus}$ planet, the eclipse produces a reduction in flux of 50%, whereas a $10 M_{\oplus}$ super-Earth would effectively block out the WD completely. It is this high contrast ratio between the planet and the host WD that makes it possible to obtain an atmospheric transmission spectrum of planets in the WDHZ with future telescopes, like the James Webb Space Telescope (JWST, Loeb & Maoz 2013; Agol 2011). The most prominent biomarker on Earth, molecular oxygen (O_2), can be detected in the transmission spectrum of an Earth-like planet orbiting WDs (see Fig. 1 in Loeb & Maoz 2013).

To detect these 2-min long transits, one must monitor at high cadence a large sample of WDs for the duration of the orbital period at 0.02 AU ($P = 30$ h). Assuming random inclinations, the transit probability is roughly 1% for Earth-size planets. To measure η_{\oplus} , the frequency of Earth-like planets, to an accuracy of 33% requires detecting 9 planets, so one must survey 10^3 WDs. Similarly, Loeb & Maoz (2013) argue that a survey of at least 500 WDs is required to detect transiting planets around them. For values of $\eta_{\oplus} < 10\%$, more stars must be observed to detect planets, so the best strategy is to observe multiple WDs simultaneously with a wide-field imager. Given the unknown

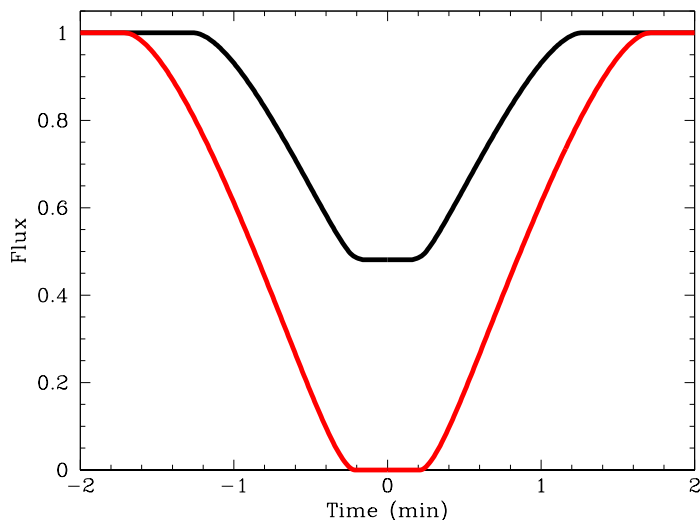


Fig. 2.— Simulation of eclipses caused by a 1 Earth mass planet (top) and a 10 Earth mass planet (bottom) transiting in the habitable zone (0.01 AU) of a white dwarf.

frequency of exoplanets in the WDHZ, a survey of $\sim 10^4$ WDs would be essential in constraining the frequency and types of planets in the WDHZ.

A ground-based telescope with a modest field of view (less than a couple sq. deg.) would have to observe the stars one at a time. So 10^4 WDs would require $2\text{-}4 \times 10^4$ days (including overhead), or about 100 years. For comparison, Kepler can perform the same survey in 200 days. There are no planned or ongoing surveys that will accomplish the survey requirements; 30 h long observations of $\sim 10^4$ WDs with 1-2 min cadence. The Transiting Exoplanet Survey Satellite (TESS) is not sensitive enough to perform a transit survey for a large number of WDs. There are also no ground-based telescopes with sufficient aperture size and wide field-of-view to perform a survey of 10^4 WDs and to obtain continuous coverage over 2 days. For example, the Large Synoptic Survey Telescope (LSST) and GAIA (Perryman et al. 2001) surveys will obtain 50 to 1000 epochs of observations over a decade, possibly detecting one epoch in eclipse for a few per cent of the WDs with transiting planets. These surveys will be biased toward detecting shorter period and larger planets that have yet to enter the WDHZ. In addition, confirmation of the planets around many of the faint LSST WDs will be challenging. On the other hand, the transits detected in our proposed Kepler survey can be easily followed-up with ground-based telescopes and, most importantly, with the JWST.

2. The Proposed Survey

Kepler in the 2-wheels mode provides an unprecedented opportunity to perform a photometric survey that is capable of finding the first exoplanets in the WDHZ. Thanks to its sky coverage and depth, for the first time, Kepler can image a large number of WDs at the same time and search for transiting planets and other substellar or stellar companions. The majority of the known WDs are

in the SDSS fields. Hence, Kepler imaging of the known WDs in the SDSS fields provides the best opportunity for such a transit survey.

There are $\approx 2 \times 10^4$ spectroscopically confirmed WDs in the SDSS DR7 area (Kleinman et al. 2013). We have identified an additional 2×10^4 WDs in the same area through proper motion measurements using the SDSS + USNO-B astrometry (Munn et al. 2004). Even though many of these targets lack spectroscopy data, Kilic et al. (2010) demonstrate that this sample is almost pure, with a contamination rate from subdwarfs of 1%. Overall, there are $\approx 4 \times 10^4$ unique WDs currently known in 11,663 sq. deg. of imaging in the SDSS DR7 area. Figure 3 shows the magnitude and color distribution of these targets. There are 10^3 and 10^4 WDs with $g \leq 16.8$ mag and $g \leq 18.7$ mag, respectively. The latter include 2253 cool WDs with $T_{\text{eff}} < 10,000$ K. We propose a Kepler imaging survey of the 10^4 SDSS WDs brighter than $g \leq 18.7$ mag to discover stellar, substellar, and planetary (including sub-earth-and-up companions) around all WDs. This survey will measure the planetary frequency and survival around both young and old systems and discover planets in the WDHZ. Thanks to the SDSS astrometry, accurate positions are known for each target and target apertures can be defined easily. The limiting factor for Kepler observations of faint sources is set by source confusion, rather than the photometric accuracy. All of our targets have SDSS imaging down to $g = 22$ mag, and the USNO-B+SDSS proper motion catalog (Munn et al. 2004) avoids sources with nearby background sources within $7''$. Hence, source confusion is not a problem for our targets. The proposed survey will image each field for 2 days, with 1 min cadence. This survey will be sensitive to planets within 0.03 AU of the stars. Imaging the DR7 area requires about 100 pointings. Hence, the entire survey can be done over 200 days.

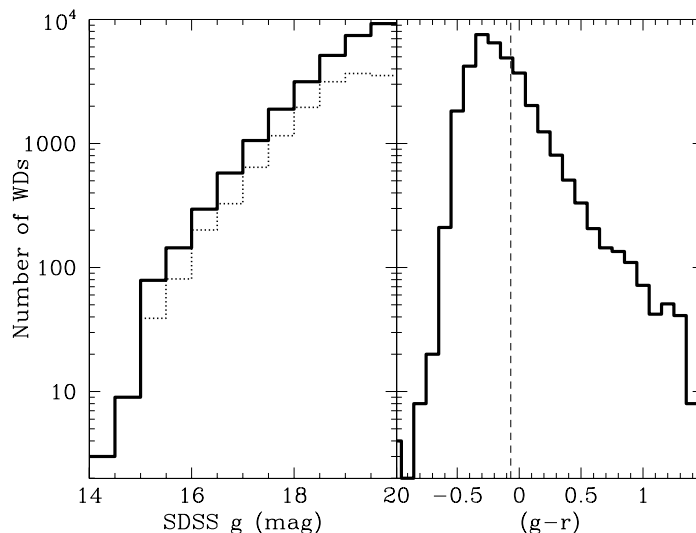


Fig. 3.— Brightness (left) and color (right) distribution of spectroscopically confirmed WDs in the SDSS DR7 (dotted line, Kleinman et al. 2013) plus high proper motion WDs (solid line, Munn et al. 2004). There are 10^3 and 10^4 targets with $g \leq 16.8$ mag and $g \leq 18.7$ mag, respectively. Objects to the right of the dashed-line (right panel) are cool WDs with $T_{\text{eff}} \leq 10,000$ K.

2.1. Kepler’s Sensitivity in the 2-Wheels Mode

The nominal Kepler mission provided ~ 50 ppm photometry for a 12 mag G2V star integrated over 30 minutes, enabling discoveries of Earth-like planets around main-sequence stars. Given the pointing problems in the 2-wheels mode, the image will be spread out over more pixels, and the increased read noise and larger responsivity variations will reduce the photometric precision to ~ 0.3 -1%. Given the eclipse signature of Earth-size and larger planets around WDs (see Figure 2), the systematic errors due to the pointing problems is not the limiting factor for WDHZ observations. Instead, the brightness of the target WDs limits the delivered photometric precision. Kepler can obtain 1% photometry for targets brighter than about 16.5 mag, and 10% photometry for targets brighter than 18.7 mag ¹. Hence, the 50% eclipse signature of an Earth-like planet can be detected at $\geq 5\sigma$ for targets as faint as 18.7 mag. It may be possible to obtain photometry of the fainter targets in the same fields by using a smaller number of pixels for computing the light curve. Figure 3 shows that the number of objects rises dramatically between $g = 18$ and 20 mag. Hence, the number of targets can easily be doubled by a ~ 0.5 mag deeper survey; operational testing of the 2-wheels mode is necessary to decide on the limiting magnitude for such observations. Kepler can effectively search for transiting Earth-size planets around 10^4 WDs in the SDSS. With its unprecedented photometric sensitivity, Kepler could also detect smaller occulting objects down to the scale of the Earth’s moon, albeit with lower significance.

3. Added Benefits

3.1. Eclipsing WD + M dwarfs: Mass-Radius Relationship

In addition to planetary companions, Kepler will also be sensitive to short period substellar and stellar companions. This sample will be essentially complete to $P = 2$ d. However, eclipsing systems with longer periods will also be detected. About 22% of field WDs have late-type main-sequence star companions (Farihi et al. 2005), while 3.4% of these systems are eclipsing with $P < 2$ day orbits (Parsons et al. 2013). Hence, the frequency of eclipsing WD + M dwarf binaries is likely around 0.75%. In a sample of 10^4 WDs, we are likely to find 75 eclipsing WD + M dwarf binaries. Earth-density planets will not survive at orbital periods shorter than 4 h. Hence, eclipses with $P < 4$ h are almost certainly from stellar or brown dwarf companions.

Given the differences in size, the eclipse signatures of WD + Earth-size planets and WD + stellar binaries would be significantly different and easy to distinguish based on the light-curves. In addition, follow-up near-infrared photometry and optical radial velocity observations of the eclipsing systems can easily distinguish between planetary companions and brown dwarf or stellar companions. Stellar binaries will show primary and secondary eclipses of different depths in different filters, offset secondary eclipses due to light travel time, gravitational lensing (Agol 2002), and

¹<http://keplergo.arc.nasa.gov/CalibrationSN.shtml>

Doppler beaming (Loeb & Gaudi 2003; Zucker et al. 2007). These systems would provide stringent constraints on the mass-radius relations for WDs and late-type M dwarfs, and also age-activity relation for the latter.

3.2. Double WDs: SNe Ia Progenitors and Gravitational Wave Sources

It is widely accepted that SNe Ia are caused by the thermonuclear explosion of WDs (Webbink 1984; Iben & Tutukov 1984), but the nature of the progenitor binary systems is not settled. Until we find the progenitors, it is impossible to understand the systematic uncertainties and to optimize SNe Ia for precision cosmology. The SNe Ia progenitor problem is therefore a key problem in astronomy today (Di Stefano et al. 2010; Howell 2011). Recent theoretical studies suggest that sub-Chandrasekhar mass WD systems may also form SNe Ia (e.g., Sim et al. 2012; Pakmor et al. 2013). Major contenders for SN Ia progenitors are mergers of binary WDs. Discovering and quantifying the population properties of close double WDs, including CO+CO and CO+He binary WD systems, can provide key insights into the SNe Ia progenitor problem (Badenes & Maoz 2012).

There are currently four eclipsing double WD systems known with orbital periods ranging from 12.75 min (Brown et al. 2011) to 5.9 h (Vennes et al. 2011). The lack of eclipsing systems at longer orbital periods is a selection effect due to the difficulty of observing a target for longer than 6 h a night. The proposed Kepler imaging survey will identify all of the eclipsing double WD merger systems among our targets, thanks to the 2 day long observations. These eclipses last 2-3 min, and include total eclipses for similar mass WDs. Based on a population synthesis model for binary stars, Agol (2011) predict a frequency of 2.5% for double WDs with $P = 8 - 64$ h. Our proposed survey will provide the first constraints on the frequency of eclipsing double WDs and their merger rate. Eclipsing double WDs provide the most accurate constraints on the masses and radii of each target. This will in turn provide the mass distribution and merger times for each system and constrain the contribution of the double degenerate channel to SNe Ia. This project may finally provide direct evidence for or against the double degenerate channel for SNe Ia.

The shortest period binary WDs are also excellent gravitational wave sources. The gravitational wave radiation and the orbital decay in the shortest period systems may be detected directly by space based missions like the Laser Interferometer Space Antenna (LISA) and indirectly by ground based observations (see Hermes et al. 2012). Nelemans (2009) lists 12 ultra-compact systems that are guaranteed LISA sources, but predicts that LISA should detect at least several hundred systems. Double WDs in the Galaxy outnumber all other known types of gravitational wave sources and they form a gravitational wave foreground. Some of the eclipsing systems found in the proposed Kepler survey will be amongst the strongest gravitational wave sources known. With accurate positions, masses, and distance estimates, these will be verification sources for gravitational wave missions in the milli-Hertz range (e.g., eLISA, Seoane et al. 2013).

3.3. Pulsating WDs

WDs go through the DOV, DBV, and DAV instability strips as they evolve. The ZZ Ceti (DAV) stars are the most common type of pulsators, with ~ 150 currently known. DAVs are found in a very well defined region in the $T_{\text{eff}} - \log g$ plane. They exhibit pulsation periods in the range 100-1400 s, corresponding to low-degree gravity-mode oscillations. The detected pulsation modes have amplitudes ranging from a few millimagnitudes to a fraction of a magnitude ($\sim 10\%$). The cooler pulsators tend to show longer periods and larger amplitudes. Also, for a given effective temperature, the observed periods tend to be longer for lower gravity objects (Gianninas et al. 2006; Hermes et al. 2013). High speed photometric studies of the pulsating WDs enable us to constrain the structure and evolutionary timescales of WDs. For example, the pulsation modes and amplitudes are sensitive to the thickness of the surface H and He layers, the depth of the convection zone, and the degree of crystallization (e.g. Montgomery et al. 2010).

There are ~ 1500 WDs with $T_{\text{eff}} \approx 12,000$ K in our proposed Kepler survey. These WDs are in the right temperature range to pulsate as a DAV. Kepler will be sensitive to large amplitude pulsations, and as a bonus, it will provide a magnitude-limited sample of pulsators. With 2 d coverage, the majority of the modes can be identified, and the most interesting targets can be followed up from the ground for further characterization and theoretical modeling of the structure of each star. Kepler will significantly increase the number of known pulsating WDs and change this field dramatically.

4. Conclusions: Why Should Kepler Observe 10^4 WDs?

Before the discovery of hot Jupiters around main-sequence stars, our view of planet formation was very different. The discovery of hot Jupiters was unexpected and unintentional. Here we outlined an alternate mission for Kepler in the 2-wheels mode targeting a large sample of WDs to find the first planets in the habitable zone. If the history of exoplanet science has taught us anything, it is that planets are ubiquitous and they exist in the most unusual places, including very close to their host stars and even around pulsars (Wolszczan & Frail 1992). Currently there are no known planets around WDs, but we have never looked at a sufficient number of WDs at high cadence to find them through transit observations. It is essentially impossible to find Earth-Jupiter size planets around WDs by any other method (Gould & Kilic 2008). If habitable planets exist around WDs, the proposed Kepler imaging survey will find them. Biomarkers, including O_2 , on such planets can be detected with the JWST. Hence, even though this is a completely unexplored search area for transiting planets, the scientific yield of the proposed survey will be enormous.

In addition to the planetary studies, the proposed survey will also dramatically change the field of short period binary WDs, including eclipsing double WDs, WD + M dwarfs, and WD + brown dwarfs. This survey will constrain the merger rate and mass distribution of double WDs, which is important for binary population synthesis studies, understanding SNe Ia explosions, and identifying new verification binaries and the Galactic foreground in gravitational waves.

Short cadence targets are limited to no more than 512 across the entire focal plane. Our proposed survey has a density of ~ 100 short cadence targets per pointing. Therefore, this survey can be combined with other projects targeting the SDSS fields. For example, similar high (or low) cadence observations of M dwarfs (e.g., the Mearth project, Berta et al. 2013) or other types of (variable) stars in the SDSS fields can be obtained simultaneously. Nearby M dwarfs can be easily selected based on their high proper motion from the SDSS + USNO-B positions (Munn et al. 2004). Alternatively, the SDSS photometry can be used to select a nearly complete and contamination free sample of variable stars like RR Lyrae over the entire SDSS footprint. The survey can also be extended to an all-sky survey through the selection of WDs from other proper motion surveys like the USNO-B, SuperCOSMOS (Rowell & Hambly 2011), and LSPM (Lépine & Shara 2005). If this survey is not selected as the primary mission for Kepler in the 2-wheels mode, it should at least be considered as a filler project for other surveys.

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