Searching for white dwarf transits with LSST

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Abstract

What happens to the planetary systems at the end of the stellar evolution is largely unknown. To date, not a single planet has been identified orbiting a (single) white dwarf (WD). Nevertheless, in the last two decades accumulating evidence has shown that the excess of metals that we see in the atmosphere of 30-40% of so called "polluted white dwarfs" is due to asteroid tidal disruption. The ongoing tidal disruption of a planetesimal has been watched live for the first time by K2 in WD1145+017. In contrast to observations of planets transiting main-sequence (MS) stars, which provide only mean densities (from mass and radius measurements) and some insight into the composition of their atmospheres, the study of debris-polluted WDs has already revealed that the bulk compositions of exo-planetary bodies resembles those found in the solar system, including evidence for water-rich planetesimals. The fact that Kepler/K2, observing in total about 500 white dwarfs, has found only one case of (irregular) transits tells us that WD transits are rare. TESS and PLATO will not improve the situation much observing about 1000 and a few thousands WDs at maximum, respectively. Much larger statistics can be obtained only with LSST, allowing – for the 1st time – to study WD transits and start understanding what happens to >95% of planetary systems (all those with a MS stellar mass below 8-10 $M_\odot$), when the host star evolves beyond the red giant phase, until it becomes a white dwarf.

1 White Paper Information

Authors: Roberto Silvotti – roberto.silvotti@inaf.it
Francesca Faedi – francesca.faedi@inaf.it

1. **Science Category:** the subject of this white paper is part of the main LSST science theme "Exploring the Transient Optical Sky" and is part of the the LSST Science Collaboration on "Transients and Variable Stars" (subgroup on Transiting Planets).

2. **Survey Type Category:** 'wide-fast-deep' (WFD) survey.

3. **Observing Strategy Category:** this program will greatly benefit from maintaining the current observing strategy of two short ($\sim$15 s) exposures per visit.

2 Scientific Motivation

What happens to the planetary systems at the end of the stellar evolution is largely unknown. Although not a single bona-fide planet has yet been identified in orbit around a single white dwarf (Hogan+2009, Faedi+2011, Fulton+2014), in recent years we have learned that many planetary systems will survive the evolution of their host stars along the giant branch (Villaver & Livio 2009) and can remain stable for many Gyr along the white dwarf (WD) cooling sequence (Mustill+2014). Small bodies, including asteroids (Jura 2003) and moons (Payne+2017), are scattered by unseen planets into the strong WD gravitational field (Debes+2012), tidally disrupt (Veras+2014), form detectable dust discs (Farihi+2009), and eventually accrete into the WD photosphere, where they can be spectroscopically detected. The ongoing tidal disruption of a planetesimal can currently be watched live in WD1145+017 (Vanderburg+2015, Gänsicke+2016, Cauley+2018). In contrast to observations of planets transiting MS stars, which provide only mean densities (from mass and radius measurements) and some insight into the composition of their atmospheres, the study of debris-polluted white dwarfs reveals the bulk composition of exo-planetary bodies (Zuckerman+2007). With about two dozen of these white dwarf systems analysed in detail, we find that the bulk compositions of rocky exo-planetary bodies resembles those found in the solar system (Gänsicke+2012), including evidence for water-rich planetesimals (Farihi+2013), and we have put an upper limit on the occurrence of exotic compositions such as planets dominated by carbon chemistry (Wilson+2016). These studies provide important constraints on theoretical models of planet formation (e.g. Carter-Bond+2012).

When a star enters the red giant branch (RGB) or the asymptotic giant branch (AGB), two opposite effects play a dominant role on the orbital evolution of its planets: stellar mass loss (planets pushed outwards) and tidal interactions (planets pushed inwards). Indeed, theoretical models predict a gap in the final distribution of orbital periods (Villaver & Livio 2007, 2009; Mustill & Villaver 2012; Nordhaus & Spiegel 2013; Villaver+2014). While Gaia DR3 will likely discover the first WD giant planets external to the period gap at several AUs or tens of AUs from their host stars (Silvotti+2015), to find those internal to the period gap remains an open challenge.

If a planet enters the envelope of an expanding giant star, its survival depends on a number of poorly constrained parameters, in particular its mass. From theory we expect that a mass of at least ≈ 10 $M_{\rm JUP}$ is needed to survive the engulfment. If we assume that only 1% of MS stars have a planet with $P_{\rm ORB} < 200$ d (in order to enter the RGB/AGB envelope) and

M>10 M$_{\mathrm{JUP}}$ (in order to survive the common envelope (CE) phase), and considering a transit probability of 0.1, corresponding to an orbital distance of 0.005 AU (or $\approx$1 R$_{\mathrm{SUN}}$) after the CE phase, we might need to observe $\approx$1000 WDs to catch one single transit.

The fact that Kepler/K2, observing in total about 500 white dwarfs, has found only one case of a WD showing (irregular) transits, likely due to disintegrating planetesimals, tells us that WD transits are not easy to detect. Partly because they are intrinsically rare, as we have seen, partly because they have a very short duration, of the order of 1-2 minutes (Fig. 1). TESS and PLATO will not improve the situation much observing about 1000 and a few thousands WDs at maximum, respectively (and the TESS cadence of 2 min will not help).

Much larger statistics can be obtained only with LSST. If the statistics is of the order of 1/1000 WDs showing transits, with LSST the number of discoveries could be $\approx$100 when considering only the 110,000 relatively bright (G<21, G=Gaia mag) WDs already identified by Gaia DR2, that fall in the WFD survey (see Fig. 2). Larger numbers will be obtained when considering also millions of new fainter WDs that will be discovered by LSST, but for these fainter stars the possibilities of high-quality follow-up (in particular spectroscopic follow-up) will be lower. The LSST potential in detecting WD transiting planets is discussed in two recent papers by Cortés & Kipping 2018 and Lund+2018.

Given that the WD transits are not only very short, but also very deep due to the small WD radii ($\sim$9,000 km for a canonical WD with log$g$=8), with LSST it will be possible – for the 1st time – to make a census of the various types of objects transiting white dwarfs, from small asteroids to giant planets and brown dwarfs, and start understanding what happens to >95% of planetary systems (all those with a MS stellar mass below 8-10 M$_\odot$), when the host star evolves beyond the red giant phase, until it becomes a white dwarf.
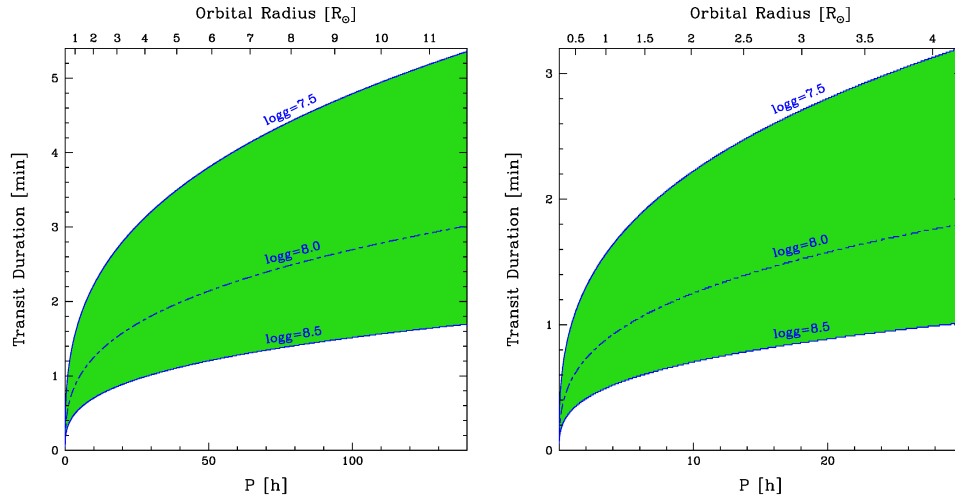
Figure 1. Transit duration for a white dwarf as a function of the orbital period. The right panel is just a zoom of the left panel in the region of short orbital periods, where we expect to find planets or planetary remnants.
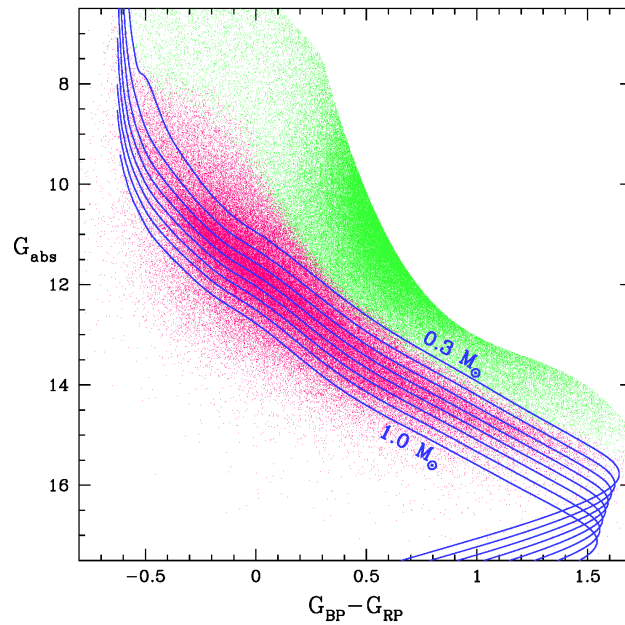
Figure 2. Gaia DR2 white dwarfs falling in the WFD field. Green+red: all the Gaia DR2 WD candidates (207,629 objects). Red: all those with $P_{WD} \geq 0.75$ (112,824 objects), where P_{WD} is the probability to be a (single) WD (see Gentile Fusillo+2018 for more details). Superimposed are the WD cooling tracks with a pure-H thick envelope from Bergeron+2011.

3 Technical Description

This programme has basically only one constraint: to keep the present observing strategy of two short ($\sim$15 s) exposures per visit. This constraint applies to all the WFD fields and ideally to all the filters, or at least to the most efficient ones.

Given that the typical duration of a WD transit is of the order of 1-2 min (see Fig. 1), to have 2 close measurements at a distance of 15-20 seconds from each other is extremely useful in order to:

a) Verify that the photometric variation is real and not simply an outlayer due to instrumental effects or other "external" reasons (i.e. not related to an intrinsic variation of the star light).

b) Not loose good candidates. A fraction of good candidates would be lost with a single 30s exposure because of the "dilution" of the photometric minima (see section 4).

c) Double the number of points in or near the transit.

d) Better distinguish a real transit from other phenomena like WD pulsations or dark spots or outbursts (more rare but not impossible in WDs). In a transit the 2 measurements will normally be significantly different (unless they fall both near the minimum) while, for other phenomena like WD pulsations or other, the difference between two close measurements is typically much smaller.

This programme will be based on the LSST alert system: an alert will be sent every time that a known WD from the Gaia DR2 catalogue will show a light decrease larger than $\approx$20%. At this point time-series photometric follow-up will be done to obtain a continuous light curve of many hours (or many light curves if needed) with a high time sampling and verify if the photometric decrease registered by LSST was actually due to a transit. Clearly the threshold of $\approx$20% is critical and will be better defined after careful evaluation. We need to find a good compromise between not loosing too many good candidates and minimizing the number of false positives.

3.1 High-level description

Just collect 2 short exposures for each visit.

3.2 Footprint – pointings, regions and/or constraints

No specific constraints on the pointings.

3.3 Image quality

No specific constraints on the seeing.

3.4 Individual image depth and/or sky brightness

No specific constraints on image depth and/or sky brightness.

3.5 Co-added image depth and/or total number of visits

Co-added images are not relevant forn this program, which makes use only of the single exposures.

The total number of visit is important and should be as high as possible, independently from the filter used (although blue filters are best suited for WDs). With ∼800 visits in 10 years (over the 6 filters), and assuming a ratio between orbital period and transit duration of 300, corresponding to an orbital period of ∼5 hours (see Fig. 1) as in WD1145+017 (Vanderburg+2015), in average 2.7 photometric measurements will fall during a transit for each WD having a planetary companion. Note that this number is multiplied by 2 if each visit consists of 2 independent exposures. And is further multiplied by the number of transiting objects if we have multi-transits like in WD1145+017. For good candidates time-series photometric follow-up will be performed to obtain a high-sampling light curve, confirm the transit, and derive orbital period, transit depth, etc. ...

3.6 Number of visits within a night

No specific constraints on the number of visits per night.

3.7 Distribution of visits over time

In general we do not have any constraint on the distribution of visits over time. However the program would benefit of earlier results if a fraction of the area of the WFD survey will be observed with a higher frequency in order to reach a high number of visits in the first 2-3 years (rolling cadence).

3.8 Filter choice

No specific constraints on filters given that transits are basically achromatic. More in general blue filters are best suited for WDs.

3.9 Exposure constraints

For the reasons listed in section 3, to have 2 short exposures per visit is the only real constraint of this project.

Saturation limits are not very critical given that the number of bright WDs is relatively small: in the WFD area only 828 WDs from the Gaia DR2 catalogue are brighter than G=16 (which is about the saturation limit for 15s exposures) and 2026 are brighter than G=16.75 ($\sim$saturation limit for 30s exposures). However it is clear that the brightest WDs are the most interesting allowing more detailed studies from high quality follow-up observations.

3.10 Other constraints

No other constraints.

3.11 Estimated time requirement

These observations are fully compatible with the standard WFD survey.

3.12 Technical trades

Not much to say about trades given that we basically have just one request of keeping 2 exposures per visit. As said in section 3.7, a "rolling cadence" would be very useful in order to start having some good candidates to be

observed with time-series photometric follow-up in the first 2-3 years of the WFD survey.

Table 1: **Constraint Rankings**

Properties	Importance
Image quality	3
Sky brightness	3
Individual image depth	2
Co-added image depth	3
Number of exposures in a visit	1
Number of visits (in a night)	3
Total number of visits	1
Time between visits (in a night)	3
Time between visits (between nights)	3
Long-term gaps between visits	2
Other (please add other constraints as needed)	

4   Performance Evaluation

Performance evaluation is not easy for this project given that it is an almost totally unknown field and there is only one case of a real light curve (WD1145+017, see section 2), which is quite irregular by the way. This is why we did not use MAF. What is clear is that having a single $\sim 30\,$s exposure per visit instead of $2\times 15\,$s exposures makes a big difference both in terms of a much larger number of false positives and also (even more important) a much larger number of non-detections of true events due to the dilution of the photometric minima. **We will try to quantify the latter point in the final version of the white paper**.

5   Special Data Processing

No special data processing is required.

6   References

Bergeron et al. 2011, ApJ 737, 28

Carter-Bond, J. C., O'Brien, D. P., Raymond, S. N., 2012, ApJ, 761, 121

Cauley, P. W, et al., 2018, ApJ Lett., 852, L22

Cortés & Kipping 2018, MNRAS submitted, arXiv:1810.00776

Debes, J. H., Walsh, K. J., Stark, C., 2012, ApJ, 747, 148

Faedi et al. 2011, MNRAS 410, 899

Farihi, J., Jura, M., Zuckerman, B., 2009, ApJ, 694, 805

Farihi, J., Gänsicke, B. T., Koester, D., 2013, Science, 342, 218

Fulton et al. 2014, ApJ 796, 114

Gänsicke, B. T., Koester, D., Farihi, J., Girven, J., Parsons, S. G., Breedt,
    E., 2012, MNRAS, 424, 333

Gänsicke, B. T., et al., 2016, ApJ Lett., 818, L7

Gentile Fusillo et al. 2018, MNRAS in press, arXiv:1807.03315

Hogan et al. 2009, MNRAS 396, 2074

Jura, M., 2003, ApJ Lett., 584, L91

Lund et al. 2018, submitted to AAS journals, arXiv:1809.10900

Mustill & Villaver 2012, ApJ 761, 121

Mustill, A. J., Veras, D., Villaver, E., 2014, MNRAS, 437, 1404

Nordhaus & Spiegel 2013, MNRAS 432, 500

Payne, M. J., Veras, D., Gänsicke, B. T., Holman, M. J., 2017, MNRAS,
    464, 2557

Silvotti et al. 2015, ASPC 493, 455

Vanderburg, A., et al., 2015, Nat, 526, 546

Veras, D., Leinhardt, Z. M., Bonsor, A., Gänsicke, B. T., 2014, MNRAS,
    445, 2244

Villaver & Livio 2007, ApJ 661, 1192

Villaver, E., Livio, M., 2009, ApJ Lett., 705, L81

Villaver et al. 2014, ApJ 794, 3

Wilson, D. J., Gänsicke, B. T., Farihi, J., Koester, D., 2016, MNRAS, 459,
    3282

Zuckerman, B., Koester, D., Melis, C., Hansen, B. M., Jura, M., 2007, ApJ,
    671, 872