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Precision astrometry of the exoplanet host candidate GD 66

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ABSTRACT

The potential existence of a giant planet orbiting within a few au of a stellar remnant has profound implications for both the survival and possible regeneration of planets during post-main-sequence stellar evolution. This paper reports *Hubble Space Telescope* Fine Guidance Sensor and US Naval Observatory relative astrometry of GD 66, a white dwarf thought to harbour a giant planet between 2 and 3 au based on stellar pulsation arrival times. Combined with existing infrared data, the precision measurements here rule out all stellar-mass and brown dwarf companions, implying that only a planet remains plausible, if orbital motion is indeed the cause of the variations in pulsation timing.

Key words: stars: individual: GD 66 – planetary systems – white dwarfs.

1 INTRODUCTION

Observations of extrasolar planetary systems in the post-main sequence have implications for the survival of the Earth and the terrestrial planets, and indirectly measure the robustness of planet formation processes. Precision radial velocity surveys are discovering a growing number of giant exoplanets orbiting post-main-sequence stars, where the hosts are either subgiant (Bowler et al. 2010; Johnson et al. 2011) or first ascent giant stars (Lovis & Mayor 2007; Sato et al. 2008; Döllinger et al. 2009; Niedzielski et al. 2009; Gettel et al. 2012). These systems have undergone relatively mild evolution compared to later stages, and their planet properties may only reflect formation processes (Currie 2009). However, it appears that the effect of star–planet tides with increasing stellar radius is non-negligible at this early stage (Villaver & Livio 2009; Hansen 2010; Lloyd 2011), and eventually becomes crucial (Nordhaus et al. 2010).

Candidate planets orbiting post-red giant branch stars are observed with varying degrees of observational evidence (Silvotti et al. 2007; Setiawan et al. 2010; Charpinet et al. 2011), but these few detections currently lack the benefit of independent confirmation (e.g. transits) and statistics that have corroborated the conventional exoplanet population. Planets orbiting these more highly evolved stars and stellar remnants provide tests of primordial planet formation, long-term star–planet and planet–disc evolution, and second generation planet formation (Melis et al. 2009; Wickramasinghe et al. 2010). The latter scenario is the only viable mechanism to produce the pulsar planets (Hansen, Shih & Currie 2009), and they remain the only post-main-sequence planets confirmed by independent means (gravitational perturbations; Rasio et al. 1992; Wolszczan 1994).

Planetary systems around white dwarfs offer a glimpse into possible futures of the Solar system (Sackmann, Boothroyd & Kraemer 1993; Duncan & Lissauer 1998; Veras & Wyatt 2012) and the opportunity to study the composition of planetary solids (Jura 2008; Farihi, Jura & Zuckerman 2009; Zuckerman et al. 2010; Gänsicke et al. 2012). Furthermore, and perhaps surprisingly, because white dwarfs outnumber A- and F-type stars in the solar neighbourhood,[1] they may represent the majority of the nearest planetary systems formed at intermediate-mass stars (!). While there have been several ground- and space-based searches for giant planets around white dwarfs (Debes, Sigurdsson & Woodgate 2005; Mullally et al. 2007; Farihi, Becklin & Zuckerman 2008; Hogan, Burleigh & Clarke 2009), to date the only published candidate comes from variations in pulsation timing of GD 66 (Mullally et al. 2008).

This paper describes interferometric and astrometric constraints on stellar and low-mass companions to GD 66 (WD 0517+307). The motivation for the study is described in Section 2, where the observational data supporting a companion are reviewed, and theoretical considerations for planet survival are explored. The *Hubble Space Telescope (HST)* Fine Guidance Sensor (FGS) and US Naval Observatory (USNO) observations are described in Section 3, and companion mass limits are derived from the analysis of these data combined with prior studies.

2 MOTIVATION

There are two lines of reasoning that led to a search for stellar-mass companions around GD 66, and each is discussed in turn below.

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The first is the continued, increasing trend in the observed pulsation arrival times, and the second is the issue of planet survival within a few au during the post-main-sequence evolutionary phases of an intermediate-mass stellar host.

2.1 Observational considerations

Mullally et al. (2008) performed photometric monitoring of 15 ZZ Ceti stars over the course of four years and identified a low-amplitude, sinusoidal variation in the expected arrival times of pulsations in GD 66. A single turnover in the observed minus calculated (or $O-C$) diagram was observed around epoch 2005.3. Assuming the pulsation frequency is perfectly stable, and that deviations in transit time are caused by orbital motion, the magnitude of this variation is given by

$$\tau = \frac{am \sin i}{cM}, \quad (1)$$

where M and m are the mass of the star and companion, respectively, a is the semimajor axis and i is the orbital inclination. This can be rewritten as a function of the orbital period p using Kepler's third law:

$$m \sin i = \tau \left(\frac{4\pi^2 c^3 M^3}{G(M+m)p^2} \right)^{1/3}. \quad (2)$$

Thus, for a given periodicity in the pulsation arrival times, the amplitude is a linear function of companion mass for $m \ll M$.

A sinusoidal fit to the GD 66 timing data was found with parameters $\tau = 3.8$ s and $p = 4.5$ yr (Mullally et al. 2008), thus implying $a = 2.4$ au and $m \sin i = 2.2\,M_{\rm Jup}$ for $M = 0.64\,{\rm M_\odot}$ (Bergeron et al. 2004). This solution predicted a turnover in the $O-C$ diagram in late 2007 that did not occur. Rather, Mullally et al. (2009) later reported that the arrival times continued to increase and a revised fit yielded $\tau \approx 5$ s, $p = 5.7$ yr, and hence $a = 2.7$ au, $m \sin i = 2.4\,M_{\rm Jup}$. This newer fit predicted a turnover in 2008 that again did not occur (Hermes et al. 2010).

Based on this trend of increasing τ, it became possible that the observed signal could be due to a stellar companion. In this case, the initial turnover discovered in the $O-C$ diagram would be a relatively low-probability event. Despite being somewhat unlikely, this alternative merits investigation due to the profound implications of a planet orbiting a stellar remnant. Stellar-mass solutions to equation (2) become plausible for $\tau > 10$ s and $i > 85°$, but existing infrared data (see Section 3.3) constrain such companions to be degenerate: brown dwarf, white dwarf or neutron star. Notably, a second white dwarf can remain hidden in optical spectroscopy if at least of comparable mass to the primary. An excellent example of this is PG 0901+140 (Farihi, Becklin & Zuckerman 2005), a 3.6 arcsec DA5+DA6 binary that exhibits an apparently single DA5.5 spectrum (Liebert, Bergeron & Holberg 2005). For such a companion mass to be viable, the increasing $O-C$ trend observed by Mullally et al. (2009) would have to continue for several years. Interestingly, orbital separations of a few to several au have been found for five double white dwarf systems using *HST* FGS observations (Nelan 2007; Subasavage et al. 2009), lending credibility to a binary scenario.

2.2 Theoretical considerations

Because GD 66 is a carbon–oxygen core white dwarf, it has passed through both the first ascent (RGB) and asymptotic giant branch (AGB) phases. Bergeron et al. (2004) give spectroscopically derived stellar parameters for GD 66 of $T_{\rm eff} = 11\,980 \pm 200$ K, $\log g\,({\rm cm\,s^{-2}}) = 8.05 \pm 0.05$, implying $M = 0.64 \pm 0.03\,{\rm M_\odot}$. Using the average of three different initial-to-final mass relations (Dobbie et al. 2006; Kalirai et al. 2008; Williams, Bolte & Koester 2009) yields a possible range of main-sequence progenitor masses between 2.2 and 2.6 ${\rm M_\odot}$. As a basic line of reasoning that favours a stellar companion over a planet at a few au, consider that the maximum AGB radius for this range of progenitor stars is in the vicinity of 3 au (Villaver & Livio 2007).

However, as explored in detail by Nordhaus et al. (2010), there are at least three processes that determine the orbital fate of low-mass companions to post-main-sequence stars such as white dwarfs: (1) orbital expansion due to mass-loss (Jeans 1924), (2) tidal dissipation of orbital energy and (3) destruction or survival in a common envelope phase. It is well known that very low mass stellar and brown dwarf companions are capable of surviving within a common envelope (Farihi et al. 2005; Maxted et al. 2006) that results from unstable mass transfer from a giant primary (Paczynski 1976), and these short-period systems are manifest among white dwarf binaries (Schultz, Zuckerman & Becklin 1996; Schreiber & Gänsicke 2003). The inward pull of tidal torques and common envelope evolution, together with the outward expansion of orbits beyond the grasp of frictional and tidal forces, effectively create a depopulated region of intermediate orbital separations (Nordhaus et al. 2010). This bimodal distribution of low-mass, unevolved companions to white dwarfs, barren from ~0.1 to ~10 au, has been empirically confirmed using high-resolution optical imaging with *HST* (Farihi, Hoard & Wachter 2006, 2010) and by spectroscopic and photometric monitoring from the ground (Nebot Gómez-Morán et al. 2011).

Following the prescription of Nordhaus et al. (2010), the relevant semimajor axis boundaries for single planets at GD 66 were computed including mass-loss, tidal forces and common envelope evolution. The main-sequence progenitor masses span the range of values expected for this system (see Section 3.1), while companion masses include the $m \sin i = 2.4\,M_{\rm Jup}$ determined from the pulsation timing analysis, and a $7\,M_{\rm Jup}$ upper limit estimated from infrared photometry and modelling (see Section 3.3; Mullally et al. 2009). Included in these calculations are the largest, initial semimajor axis for planets directly engulfed by the AGB star, and the smallest, final semimajor axis for planets that avoid being swallowed. Planets are destroyed in the first instance, while in the latter case their orbits are strongly influenced by tides yet just avoid the giant envelope. It is found that for a wide range of possible tidal prescriptions, all companions that avoid engulfment end up in $a \geq 3.6$ au orbits, and all but the most finely tuned initial conditions lead to final separations several au larger. Therefore, an extant planet at 2−3 au around a white dwarf remnant of a $M \geq 2.2\,{\rm M_\odot}$ main-sequence star would require an unexpected evolutionary scenario (e.g. capture or re-formation). These predictions imply that a planet is rather unlikely, and largely prompted a search for stellar-mass objects capable of producing the sinusoidal timing variations observed by Mullally et al. (2008).

3 OBSERVATIONS AND DATA

3.1 USNO astrometry

Optical CCD observations of GD 66 spanning just over a decade were carried out as part of the USNO faint star parallax programme. Imaging photometry was collected for the purposes of correcting for differential colour refraction and to measure an absolute trigonometric parallax. In practice, because observations were taken within (and usually much less than) 1 h of meridian, differential colour refraction was minimal. A complete discussion of the astrometric data

Table 1. USNO observations of GD 66 over 10.25 yr.

Astrometry:	
$\pi_{\rm rel}$	16.86 ± 0.16 mas
$\pi_{\rm ref}$	0.97 ± 0.12 mas
$\pi_{\rm abs}$	17.83 ± 0.20 mas
μ_α	$+55.3 \pm 0.1$ mas yr^{-1}
μ_δ	-120.3 ± 0.1 mas yr^{-1}
$v_{\rm tan}$	35.2 ± 0.4 km s^{-1}
Photometry:	
V	15.56 ± 0.02 mag
$B - V$	$+0.13 \pm 0.02$ mag
$V - I$	-0.05 ± 0.02 mag
M_V	11.82 ± 0.02 mag

Note. Photometry is on the Johnson–Cousins system and given in Vega magnitudes. Conservative errors for these mean magnitudes are 0.02 mag.

acquisition and reduction can be found in Dahn et al. (2002). Briefly, the observations were taken using the USNO 1.55 m Strand Astrometric Reflector and Tektronix 2048 × 2048 camera with 24.0 µm pixels at 0.325 arcsec pixel^{-1}. These observations employed a wide *R*-band filter, similar to that described in Monet et al. (1992). Independent photometry in the Johnson *BV* and Cousins *I* band was collected on two nights at the USNO 40-in telescope. Photometric standards of various colours from Landolt (1992) were taken at multiple air masses to correct for extinction and colour terms.

The USNO astrometric results are listed in Table 1, placing GD 66 at $d = 56.1^{+0.6}_{-0.5}$ pc, and yielding an absolute visual magnitude of $M_V = 11.82$ mag. Comparing this with the spectroscopically derived value of $M_V = 11.75$ mag based on $T_{\rm eff} = 11\,980$ K (Bergeron et al. 2004), the parallax favours a slightly higher mass. Using this same effective temperature, white dwarf atmospheric models yield $\log g = 8.09$, $M = 0.66\,{\rm M}_\odot$, and a cooling age of 420 Myr (Fontaine, Brassard & Bergeron 2001). Although the astrometric data presented here do not constrain the temperature of GD 66, the ZZ Ceti instability strip is narrow at $\Delta T_{\rm eff} \approx 1000$ K for $\log g \approx 8.1$ (Gianninas, Bergeron & Fontaine 2005). To within the errors introduced by its few per cent photometric variability (Fontaine et al. 1985), the optical *BVI* photometry of GD 66 yields colours precisely as expected for a DA white dwarf of the published effective temperature.

Fig. 1 plots the astrometric residuals for each observing season after subtracting the proper motion and parallax, demonstrating a few mas precision. This relative astrometry is sensitive to orbital motion induced by an *optically dark* companion. Notwithstanding the systematically noisier residuals in declination relative to those in RA, the astrometric monitoring of GD 66 should have detected a 3σ deviation of 3 mas due to orbital motion in the plane of the sky. Fig. 2 marks this detection threshold in a plot of the astrometric excursion as a function of companion mass for several benchmark orbital periods in a circular binary configuration. These mass limits are independent of orbital inclination for circular orbits, and degrade only in the specific case of an eccentric orbit at high inclination with line of apsides near to the line of sight ($\omega \approx 90°$).

Because the astrometric companion sensitivity only diminishes for finely tuned orbital parameters, the USNO data rule out all $m \gtrsim 50\,M_{\rm Jup}$ ($0.05\,{\rm M}_\odot$), optically faint companions, including very low mass stars, neutron stars and black holes, for orbital periods $p > 4$ yr. Remarkably, a period-dependent range of relatively low, brown dwarf companion masses can be similarly ruled out for longer periods up to 20 yr. However, these data provide little or

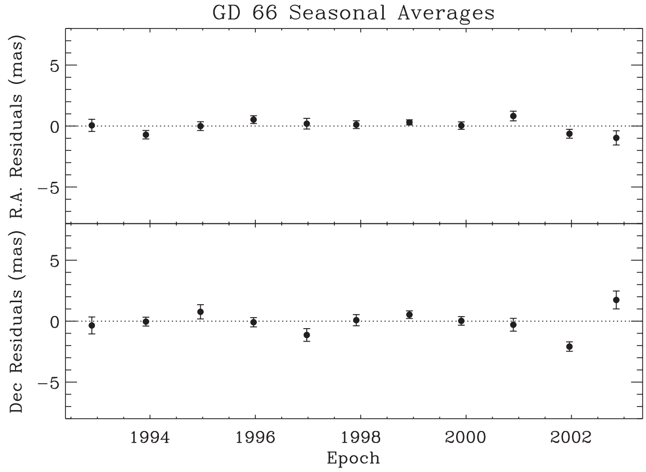

Figure 1. Residuals obtained after fitting proper motion and parallax to the USNO astrometric observations of GD 66. Shown are the seasonal averages and the standard error of the mean. A total of 172 frames taken on 151 nights were used in the parallax solution, with 9–32 observations per season. The behaviour of the residuals in declination are also observed in a field star near to GD 66 on the CCD, and are thus systematic.

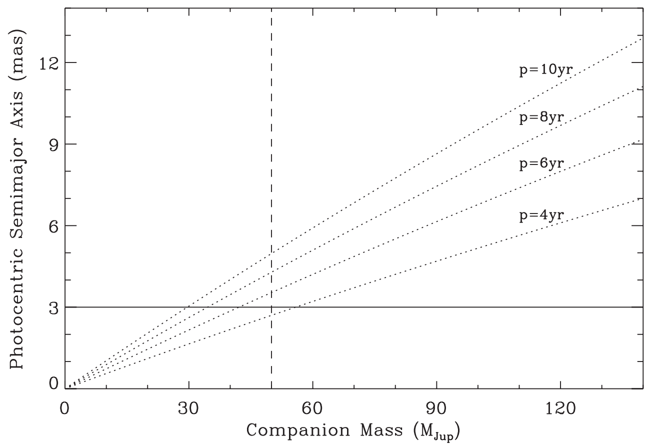

Figure 2. Companion mass sensitivity for primary mass $0.66\,{\rm M}_\odot$ and a 3σ threshold of 3 mas deviation due to circular orbital motion for GD 66. Plotted as dotted lines is the astrometric excursion as a function of companion mass for several benchmark orbital periods. The dashed line corresponds to a detectable companion mass of $50\,M_{\rm Jup}$ at nearly all orbital periods between 4 and 20 yr. For circular motion, the companion mass sensitivity is immune to orbital inclination, and thus the USNO astrometry rule out a wide range of low-mass, stellar and substellar companions capable of producing the $O-C$ variations.

no constraints on white dwarf companions in this mass range, as a binary of equal mass and brightness will exhibit no photocentre shift.

3.2 FGS interferometry

GD 66 was observed during *HST* Cycle 18 on 2010 October 6 by FGS1r in its high angular resolution transfer mode, using the F538W filter which covers 4500–7000 Å. In this mode FGS1r repeatedly scans an object and provides data from which interference fringes along its two orthogonal axes can be reconstructed (Nelan 2011). A relatively bright comparison star known to be a point source at FGS resolution, BD+84 12, was observed as a calibration source. Fig. 3

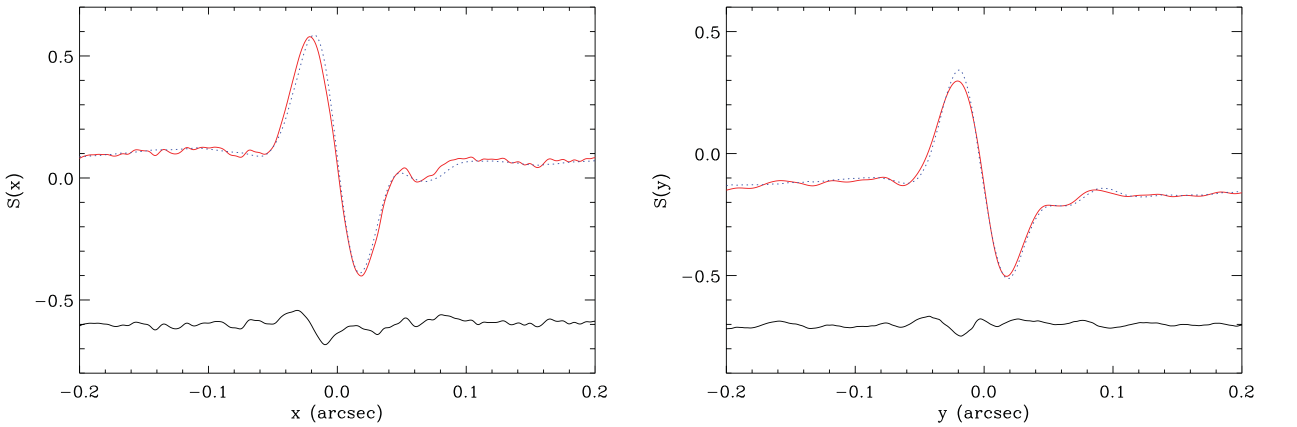

Figure 3. Interference fringes for GD 66 along the FGS1r x and y axes. The fringes of the science target are shown as solid red lines and do not differ significantly from that of the calibration point source, BD+84 12, shown as dotted blue lines. At the bottom of each panel are shown the residuals in black, which arise from photometric noise, indicating that GD 66 is unresolved. These data rule out stellar companions at $\Delta m = 2.44$ mag in F538W with separations greater than 10 mas, or 0.56 au at the trigonometric parallax distance.

plots the FGS data for GD 66 and calibration star, and reveals that the white dwarf is unresolved to 10 mas and $\Delta m = 2.44$ mag.

The FGS interferometry is sensitive to white dwarf companions at nearly all possible orbital separations and inclinations. While two equal mass degenerates would be readily detected down to 0.56 au and $p = 0.4$ yr, such short periods are not consistent with the $p > 4$ yr, pulsation timing variations of GD 66. For the periods fitted to the timing data of GD 66, equation (1) dictates that a stellar-mass companion should be within several degrees of face-on. Therefore, the FGS data would have readily detected orbital separations from a few to several tens of au, and thus rule out companions of comparable brightness and mass. However, in the very low-probability event that the $O-C$ turnover was a 1 in 10^5 chance detection, the FGS data also constrain a putative double degenerate binary for any inclination. If the observed $O-C$ minimum in 2005.3 corresponds to a binary system in conjunction as seen from the Earth, then the projected separation of the stars has been widening since, yet must still have an angular separation below 10 mas = 0.56 au from its non-resolution by FGS in 2010.8. This implies a system period greater than 10^5 yr for edge-on orbits and total system masses $M \gtrsim 1\,M_\odot$. All double white dwarfs with shorter periods would have had a wider projected separation and been detected by the FGS.

Importantly, white dwarf secondaries fainter than the primary by $\Delta V > 2.4$ mag are not feasible by normal, unperturbed stellar evolution; the total system age is insufficient to achieve such low luminosities. From the $0.66\,M_\odot$ white dwarf mass derived from the trigonometric parallax, the main-sequence progenitor of GD 66 had a mass between 2.4 and $2.8\,M_\odot$ (Dobbie et al. 2006; Kalirai et al. 2008; Williams et al. 2009), a hydrogen-burning lifetime in the range 460–660 Myr (Hurley, Pols & Tout 2000) and a total system age of 0.9–1.1 Gyr. Any cool and massive white dwarf (total age ≈ cooling age) can become no fainter than $M_V = 13.9$ mag over 1.1 Gyr (Fontaine et al. 2001) and would be detectable as $\Delta V < 2.1$ mag.

3.3 Infrared photometry

Existing *Spitzer* IRAC photometry of GD 66 are sensitive to substellar companions that would not be detected by the USNO or FGS optical astrometry. Mullally et al. (2009) used these infrared observations to estimate an upper limit on spatially unresolved (within 2.4 arcsec ≈ 130 au), self-luminous objects of $7\,M_{\rm Jup}$, thus indicating that the putative companion should have a planet-sized mass. Their method utilized observations of three white dwarfs with similar temperatures to constrain the photospheric flux ratio between 3.6 and 4.5 µm, reporting a 1σ total uncertainty of 0.6 per cent in the ratio observed for GD 66. As an example of an alternative method using IRAC photometry, Farihi et al. (2008) established substellar companion mass limits at 15 per cent above the predicted (or measured) 4.5 µm photospheric flux. Applying this procedure to GD 66 with the USNO parallax distance, a total system age of 1 Gyr (see Section 3.2), and assuming its 4.5 µm flux measurement (Mullally et al. 2009) is due to the photosphere, one obtains an upper limit of $11\,M_{\rm Jup}$ (Baraffe et al. 2003). If one insists on only a 10 per cent excess at this wavelength, the upper limit drops to $9\,M_{\rm Jup}$. It should be mentioned that all such analyses depend on atmospheric models, none of which have empirical constraints at these masses, as well as the adopted total system age. Regardless of the method, the infrared data rule out all but planetary masses, according to models.

4 CONCLUSION

The combined observational data on GD 66 limit any binary companions orbiting within several au to planetary masses. Specifically, any long-term, increasing trend in the pulsation arrival times cannot be due to stellar-mass secondaries, which include low-mass stars, white dwarfs, neutron stars and black holes with periods longer than 4 yr. The USNO relative astrometric monitoring of just over a decade rules out stellar-mass, dark companions with periods between 4 and 20 yr, while the FGS observations rule out virtually all white dwarf companions, regardless of orbital inclination. Based on substellar cooling models, infrared data further restrict low-mass companions within 100 au to have planetary masses. It is noteworthy that the trigonometric parallax and infrared photometry by themselves rule out a range of double degenerate scenarios, but the astrometric monitoring and interferometry provide significantly more stringent limits to such binaries.

If the observed timing data at GD 66 are due to orbital motion, these new and exciting data rule out a vast range of realistic companion masses, and strengthen the likelihood of a planet-sized mass as the cause. Because stellar evolution models and resulting star–planet interactions indicate that a planet within a few au of an intermediate-mass star is not likely to survive to the white dwarf stage, the putative planets at GD 66 and other post-RGB stars V391 Peg and KPD 1943+1405 (KOI 55), if real, may have been dynamically injected or formed in a second generation of planet formation. Further study of these and future post-RGB planet candidates is needed to better understand the population and architecture of planetary systems around white dwarfs.

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