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Detectability of Substellar Companions Around White Dwarfs with Gaia

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Abstract. To date not a single-bona fide planet has been identified orbiting a single white dwarf. In fact we are ignorant about the final configuration of >95% of planetary systems. Theoretical models predict a gap in the final distribution of orbital periods, due to the opposite effects of stellar mass loss (planets pushed outwards) and tidal interactions (planets pushed inwards) during the RGB and the AGB stellar expansions. Over its five year primary mission, Gaia is expected to astrometrically detect the first (few tens of) WD massive planets/BDs giving first evidence that WD planets exist, at least those in wide orbits. In this article we present preliminary results of our simulations of what Gaia should be able to find in this field.

1. Introduction

In recent years, the question of the planet survivability during the post-MS evolution has attracted some interest and the first models were computed (Villaver & Livio 2007, 2009; Nordhaus et al. 2010; Passy et al. 2012; Spiegel 2012; Mustill & Villaver 2012; Nordhaus & Spiegel 2013; Villaver et al. 2014). When the host star experiences the red giant or asymptotic giant expansion, the interplay between stellar mass loss and tidal effects determine whether the planetary orbits expand (when stellar mass loss dominates) or shrink (when tidal effects dominate). In this game various parameters like the planetary mass, the initial semi-major axis and the eccentricity are crucial. At the end of the evolution, when the star becomes a white dwarf (WD), we expect therefore that some planets have migrated outwards and some inwards, so that the final distribution of orbital periods shows a gap. Close to the star we expect to find only massive companions in very tight orbits (those for which the initial planetary mass was large enough to survive the common envelope phase), while all the other planets were presumably pushed out at several AUs from their host star.

Most of the known planets orbiting Main Sequence (MS) or subgiant stars have been detected through Radial Velocities (RVs) or transits. For white dwarfs, the small number of narrow lines limits the precision that we can reach with the RV technique. For what concerns transits, the small WD radii are at the same time and advantage and a limit, implying very deep transits (objects smaller than the Moon could easily be detected), but also very small transit probabilities. The only sistematic attempt to detect WD planetary transits gave no positive results (Faedi et al. 2011, Braker et al. these proceedings). In fact only objects very close to the star can be detected from their transit signature and/or from the reflex motion they cause to the star, if these objects are massive enough (tens or Jovian masses, see e.g. Maxted et al. 2006). For what concerns distant planets, those outside the period gap, direct imaging is not the solution (see Hogan et al. 2009), being efficient only for very young objects: it could work only for 2nd generation planets if such planets exist. Pulsation timing has proved to have serious problems (Dalessio et al. 2013 and these proceedings) but remains interesting at least to set upper limits to the planetary frequency around WDs (Don Winget et al. these proceedings). Eclipse timing is more reliable (at least in one case, NN Ser, it is giving interesting results, Beuermann et al 2013, Marsh et al. 2014 and these proceedings, Parsons et al. 2014), but is limited only to circumbinary planets orbiting eclipsing systems. The most promising method to detect WD planets in wide orbits is certainly the astrometry and the recent successful launch of Gaia suggests that in the coming years major improvements in this field will be achieved. In this context we have started a work to simulate what Gaia can find.

2. Gaia Astrometric Detections

2.1. Preliminary results

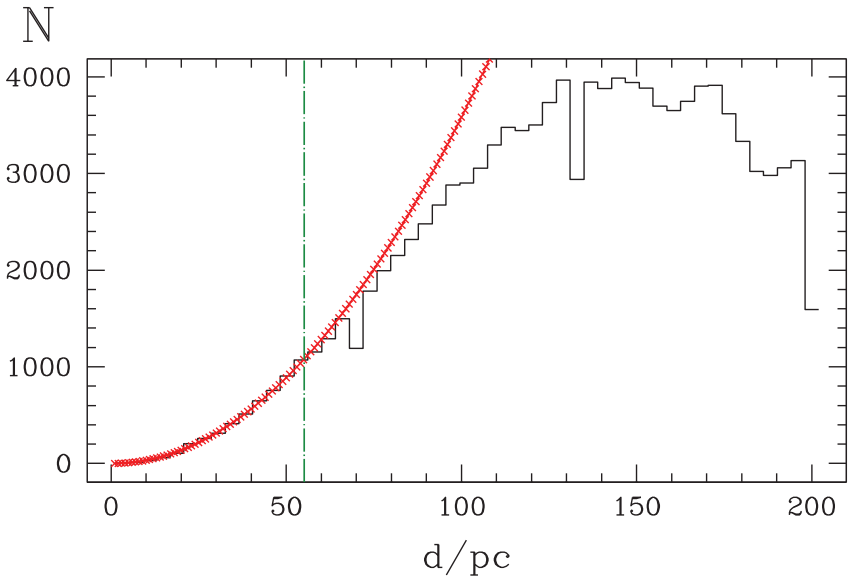

Figure 1. White dwarf distribution as a function of distance. The expected trend assuming a constant space density without any cutoff in magnitude is shown (red in the electronic version). The vertical (green) line represents the completeness limit.

First we have built up a WD catalogue using the Besançon galaxy model (Robin et al. 2003)[1], including 4 populations (thin and tick disk, spheroid and bulge) and

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[1] *http://model.obs-besancon.fr/*

kinematics, but excluding binaries. Limiting our catalogue in magnitude (R<20.5) and distance (d<200 pc), the total number of objects is 116,295 with a completeness limit near 55 pc (Fig. 1). Our simulations are based on the double-blind set-up by Casertano et al. (2008), considering 5 years of nominal mission and using a pre-launch error model. We have considered 5 mass ranges for the companion: 1–3, 3–7, 7–13 and 17–80 M_{Jup}. Up to 17 M_{Jup} the frequency of planets in the MS follows a power law: $dN \propto M^{\alpha} P^{\beta} dlnM\ dlnP$ with $\alpha = -0.31$ and $\beta = 0.26$ (Cumming et al. 2008). From 17 to 80 M_{Jup} we have used a uniform distribution with an integral frequency of 0.5% (Ma & Ge 2014). We have then considered orbital periods in MS larger then 0.4 years with all the other orbital elements following a uniform distribution in their full range of values, except for the eccentricity which varies between 0 and 0.6. Finally, we have assumed that during the evolution from the MS to the WD cooling track, the orbits have expanded by a constant factor 2.5 (corresponding to the stellar mass loss of a star with a MS mass of 1.5 $M_{\odot}$). No tidal effects were considered. This very simple scheme of orbital expansion is in some way coherent with an intrinsic limitation of the catalogue obtained from the Besançon galaxy model, in which the mass of all white dwarfs is assumed to be constant and equal to 0.6 $M_{\odot}$. These aspects will be improved in the next set of simulations in which a new catalogue with more realistic WD masses will be used.

The efficiency of the astrometric planet detection for a companion mass of 5, 15 and 50 M_{Jup} respectively, is shown in Fig. 2. In Table 1 we summarize our results.

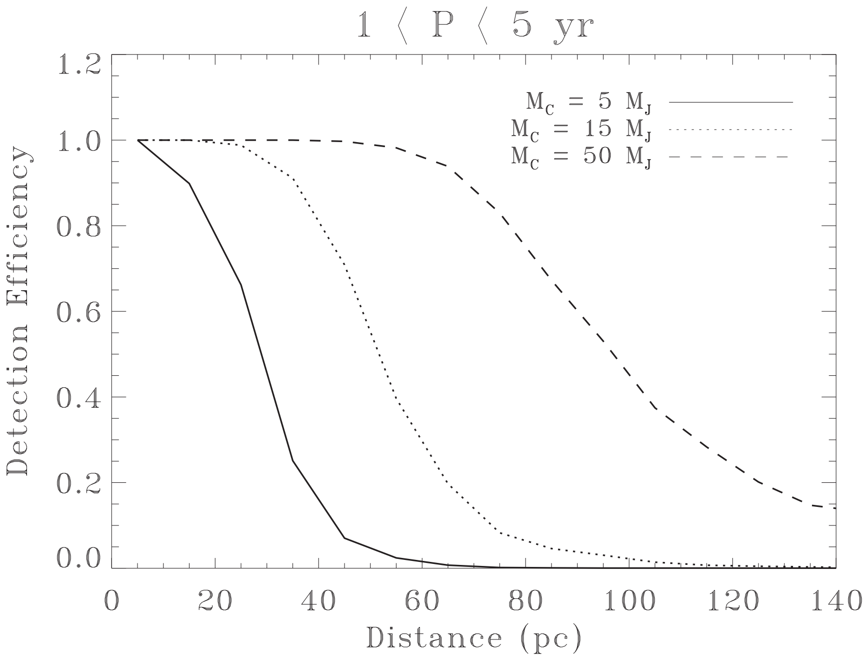

Figure 2. Gaia detection efficiency curves at S/N>3, corresponding to a 99.9% confidence level (see Sozzetti et al. 2014 for more details). The typical errors on companion mass recovery are 20-30%.

Table 1. Gaia simulations results

	$P_{\rm ORB}$=1-2 yrs	$P_{\rm ORB}$=2-3 yrs	$P_{\rm ORB}$=3-5 yrs	TOT (1-5 yrs)
1-3 $M_{\rm Jup}$	0	0	0	0
3-7 $M_{\rm Jup}$	2	1	0	3
7-13 $M_{\rm Jup}$	5	4	0	9
13-17 $M_{\rm Jup}$	14	8	4	26
17-80 $M_{\rm Jup}$	71	14	21	106

2.2. Future work

The results summarized in Table 1 show that Gaia is more sensitive to substellar companions with orbital periods between 1 and 2 years.[2] However, recent theoretical results show that the outer limit of the period gap is expected to be near 2 yrs (Mustill & Villaver 2012). Thus it is likely that Table 1 overestimates the number of planets/BDs with orbital periods shorter than ~2 years. This problem will be partly solved with a new series of simulations that will make use of a new catalogue in which more realistic WD and progenitor masses will be considered. An other improvement that we are considering is to take into account tidal effects during the RGB/AGB stellar expansion.

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[2] This fact, apparently in contradiction with the power-law frequency of MS planets and with the detection efficiency of Gaia, which increases at longer periods, is related to the assumed rigid orbital expansion (constant factor of 2.5) caused by the stellar mass loss, which redistributes the orbital periods and pushes the MS periods exceeding 2 years beyond the upper limit considered of 5 years.