The Way To a Double Degenerate: $\sim 15 - 20$ per cent of $1M_\odot \leq M \leq 8M_\odot$ Stars have a $M > 1M_\odot$ Companion

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ABSTRACT
We find that $\sim 15 - 20$ per cent of A-type stars or red giants are bound with a massive companion ($M_{\text{secondary}} > 1M_\odot$) in an intermediate wide orbit ($0.5 < P < 5000$ yr). These massive binaries are expected to form wide-orbit, double-degenerate systems (WODDs) within $\lesssim 10$ Gyr implying that $\sim 10$ per cent of white dwarfs (WDs) are expected to be part of a WODD with a lighter WD companion. These findings are based on an analysis of previous adaptive optics observations of A-type stars and radial velocity measurements of red giants and shed light on the claimed discrepancy between the seemingly high multiplicity function of stars and the rather low number of detected double degenerates. We expect that GAIA will find $\sim 10$ new WODDs within 20 pc from the sun. These results put a stringent constraint on the collision model of type Ia supernovae in which triple stellar systems that include a WODD as the inner binary are required to be abundant.

Key words: White Dwarfs – Binaries: general – Supernovae: Type Ia

1 INTRODUCTION
Type Ia Supernovae (SNe) are among the most luminous and energetic events observed. Following decades of extensive observational surveys and modeling efforts, there is good evidence that these events are the result of thermonuclear explosions of carbon oxygen white dwarfs (CO-WDs) but it is still unknown what triggers $\sim 1$ per cent of them to explode (for a recent review, see e.g. Maoz et al. 2014).

One of the scenarios recently argued to be the progenitor of type Ia SNe is the direct collision (as opposed to merger) of two CO-WDs (Katz & Dong 2012; Kushnir et al. 2013; Dong et al. 2015). Following previous demonstrations that colliding WDs explode (Rosswog et al. 2009; Raskin et al. 2010; Hawley et al. 2012), Kushnir et al. (2013) showed numerically that such collisions with the observed range of WDs masses robustly lead to thermonuclear explosions with the observed range of brightness and late time characteristics. Dong et al. (2015) reported observations of double peaks in the spectra of some events, a unique prediction (so far) of the collision model.

Until recently, the rate of direct collisions was considered to be orders of magnitudes lower than the type Ia rate (e.g. Rosswog et al. 2009; Raskin et al. 2009). Thompson (2011) recently argued that the merger rate of WDs due to gravitational waves may be enhanced in triple systems by the Lidov-Kozai mechanism and noted that some direct collisions may also occur in such systems. It was later shown by Katz & Dong (2012) that the rate of WD direct collisions may be as high as the type Ia rate if tens of per-cents of WDs reside in (mildly) hierarchical triple systems with a wide-orbit-double-degenerate (WODD hereafter) inner binary (semimajor axis $1 \lesssim a_0 \lesssim 1000$AU), raising the possibility that most type Ia SNe are due to direct collisions.

A critical requirement for the collision model is that a sufficient amount of triple systems with the required hierarchy exists. In particular, such systems should have an inner WODD. A first step to determine the abundance of such relevant triple systems is to find out the abundance of WODDs. In this paper we therefore attempt to answer the following question: what is the fraction of CO-WDs that have a lighter CO-WD companion with a wide orbit ($P \gtrsim 1$ yr)?

A straightforward approach to answer this question is to examine the population of WDs in the solar neighborhood. This approach was presented in Holberg (2009) based on the local sample of WDs within $D < 20$ pc claimed to be 80 per cent complete by the authors (Holberg et al. 2008). In this sample, there are only 3 WODDs2 out of 136 WDs

1 The sample has been updated to 136 WDs without any new WODDs and its current completeness estimate by the authors is 86 per cent (Holberg et al. 2016).
2 WD-0121-429 is an additional uncertain candidate. One should
in total. This count suggests that only \( \sim 2 \) per cent of WDs have a (lighter, wide orbit) WD companion (and only \( \sim 30 \) per cent have any companion (Holberg et al. 2016)).

This result is very low compared to the binarity fraction (\( \sim 70 \) – \( 100 \) per cent) of the progenitors of todays WDs - intermediate mass main sequence (MS) stars (\( M \sim 1.5 \) – \( 8M_\odot \), e.g. Kobulnicky & Fryer 2007; Kouwenhoven et al. 2007) and their supposed mass ratio distribution of \( f(q) \propto q^{4.5} \). Moreover, 4 out of the closest 6 WDs are in binary systems (Holberg et al. 2016) and the two closest WDs - Sirius B and Procyon B have massive (\( M \gtrsim 1.5M_\odot \)) MS companions that will become WDs within \( \sim 1 \) Gyr and are thus likely to become WO DDS (Liebert et al. 2005, 2013). If the fraction of WODDs is indeed \( \sim 2 \) per cent, this is a strange (but possible) coincidence. Another option is that for some reason, many of the wide-orbit MS massive binaries do not end up as WODDs. Interaction during the stellar evolution is unlikely to play a significant role beyond separations of a few AU and we assume that bound systems remain bound (however see comment about this assumption in section § 4). These puzzles have led to suggestions that Holberg et al. (2008) is not as complete as reported by the authors (Ferrario 2012; Katz et al. 2014).

In this paper we attempt to quantify the expected fraction of WODDs based on observations of the relevant WD progenitors - intermediate mass (\( 1 < M < 8M_\odot \)) MS stars that will become WDs within a Hubble time. An adaptive optics (AO) survey of A-type stars within 75 pc was recently conducted by De Rosa et al. (2014) allowing the binarity fraction at long periods (\( P \gtrsim 50 \) yr) to be established. In particular the relevant massive (\( M_\text{secondary} > 1M_\odot \)) companions have sufficiently low contrast to be reliably detected. This is discussed in section § 2. The fraction of companions with shorter periods is more challenging. Finding binaries with periods \( P \sim 1 \) – \( 10 \) yr is currently best achieved by radial velocity (RV) surveys. However, the rapid rotation of the relevant intermediate mass stars broadens the lines and makes it very challenging (Verschueren et al. 1999). A way around this problem is to observe these stars when they are in the red giant phase in which the rotational broadening is greatly reduced. An extensive RV survey of red giant stars in open clusters was preformed by Mermilliod et al. (2008) providing an excellent sample. Again, the fact that only companions with significant mass are considered implies large signals increasing our confidence of detection. An analysis of the sample is done in section § 3.

We find that \( \sim 15 \) – \( 20 \) per cent of massive stars have a (lighter) massive companion \( M_\text{secondary} > 1M_\odot \) in the period range \( 0.5 \leq P \leq 5000 \) yr with a uniform distribution in logarithmic space or equivalently \( \sim 4 \) per cent per dex in period (see Fig. 4). A roughly flat distribution in log space is typical for wide binaries (e.g. Raghavan et al. 2010) and the fact that such a distribution is obtained increases our confidence in the estimate which is based on very different samples at the two ends of the period range which covers 4 orders of magnitude.

2 ADAPTIVE OPTICS MEASUREMENTS OF A-TYPE STARS

De Rosa et al. (2014) conducted an adaptive optics (AO) survey of 363 A-type stars (identified by photometric colour and brightness by Hog et al. (2000)) drawn from a volume limited sample selected from the Hipparcos catalogue (ESA 1997; van Leeuwen 2007) within 75 pc from the sun. The distance distribution of the Hipparcos sample indicates that it is complete within \( D \leq 50 \) pc (De Rosa et al. 2014). The massive companions with \( M_\text{secondary} > 1M_\odot \), have a contrast in \( K \)-band of \( \Delta m < 3 \) mag compared to the A-type stars primaries. Therefore, according to fig. 8 of De Rosa et al. (2014) such massive binary systems are detectable with confidence \( \geq 80 \) per cent for an angular separation range of \( 0.3 \leq \rho \leq 15 \) arcsecs, corresponding to projected separations of \( 15 \leq a_{\text{proj}} \leq 750 \) and \( 9 \leq a_{\text{proj}} \leq 450 \) AU at \( D = 50 \) and \( 30 \) pc respectively. We henceforth consider only systems with \( 30 < D < 50 \) pc, obtaining a rather complete survey for a conservative projected separation range of \( 20 \leq a_{\text{proj}} \leq 420 \) AU corresponding to a period range of \( 50 < P < 5000 \) yr. There are 179 A-type stars in the Hipparcos catalogue in this range and our sample consists of the 121 among these that were observed by AO. The period histogram of companions to the A-type stars observed by the AO survey within \( 30 < D < 50 \) pc is shown in Fig. 1 using masses estimated by De Rosa et al. (2014). We find that \( \sim 4 \) per cent of A-type stars have companions with \( M_\text{secondary} > 1M_\odot \) in each of the logarithmic orbital period bins \( 50 < P < 500 \) and \( 500 < P < 5000 \) yr. For the period bin of \( 5 < P < 50 \) yr we find a lower limit of massive binarity fraction of \( \sim 2 \) per cent. While we are interested in separations \( a < 1000 \)AU, we note that in addition to the AO survey, De Rosa et al. (2014) reported common proper motion (CPM) binaries at larger separations \( a \gtrsim 3000 \)AU (\( P \gtrsim 10^3\) yr) and found only one companion with \( M_\text{secondary} > 1M_\odot \) in this range. The total binarity fraction (including all companions) is decreasing for such wide separations as shown there (fig. 9).

3 RADIAL VELOCITY MEASUREMENTS OF RED GIANTS

Binaries with low projected separations \( \rho \lesssim 0.1 \) arcsecs are not resolved by the AO survey. Accurate radial velocity measurements of intermediate mass MS stars \( 2 \leq M \leq 8M_\odot \) is challenging to obtain due to their typical fast rotation (Verschueren et al. 1999). This problem can be bypassed by

\[ P = \frac{t_{\text{orb}}}{2M_1M_2/M_1^2 + M_2^2} \]
observing the stars during their red giant phase where accurate RV measurements can be obtained. Red giants in open clusters are particularly useful given their known distance and the fact that their mass can be inferred from the age of the cluster.

An extensive RV survey of red giants in open clusters was concluded in Mermilliod et al. (2008) who obtained 10517 measurements of 1309 red giants over ~15 years. We limit our analysis to the sample of red giants marked as members of open clusters (with a known age) by Mermilliod et al. (2008) and measured more than once, resulting with 797 giants. Orbital solutions for binary systems with $P < 15$ yr were obtained and presented in Mermilliod et al. (2007). The amount of companions in the period range $0.5 < P < 5$ yr is shown in Fig. 2 as a function of the primary mass. The primary mass is estimated as

$$M_{\text{Red giant}} = 10^{1.3} M_\odot (\text{Age/Myr})^{-1/3}$$  

where the ages of the clusters are adopted from Dias et al. (2014). Given that the primary’s mass is known but the inclination of the orbit is not, the RV observations provide a lower limit for the companion’s mass. The numbers of binaries with a minimal companion’s mass above $1M_\odot$ are shown in the figure. As shown in the figure, 29 out of the 797 red giants observed, ~3.6 yr percent, are bound in an orbit with period $0.5 < P < 5$ yr and a companion with a minimal mass of $1M_\odot$.

Massive companions can be missed in this survey for two main reasons: 1. The inclination is too high so that while the companion’s mass was above the threshold of $1M_\odot$, the derived minimal mass was not. 2. The RV signal’s amplitude was not high enough to allow for a detection and accurate solution and the system was misclassified. As we next show, the real fraction of massive companions is likely ~1.3–2.1 times larger than the observed fraction of systems with $M_{\text{minimal}} > 1M_\odot$ implying a fraction of ~5–8 per cent.

The probability that the derived minimal mass for the secondary is lower than $1M_\odot$ is plotted in Fig. 3 as a function of the secondary’s (‘real’) mass, assuming an isotropic orientation distribution (uniform distribution in $-1 \cos i \leq 1$) for several typical values of the primary’s mass. As can be seen in the figure, the probability that a companion with a mass of $M_{\text{secondary}} = 2M_\odot$ has an inclination that leads to a derived minimal mass $< 1M_\odot$ is $<0.2$. Naturally, the lower the companion’s mass (above $1M_\odot$) the higher the chance to miss it due to high inclination. The fraction of massive binaries that result with a derived minimal mass $< 1M_\odot$ due to inclination can be estimated given an assumed mass ratio distribution. We consider two mass ratio distributions: a. Uniform - $dN/dq = \text{const.}$ (e.g. Raghavan et al. 2010) b. ‘Kroupa IMF’ - $dN/dq \propto q^{-2.3}$, which is obtained if the mass of the companion is drawn from the Initial mass function (IMF) suggested by Kroupa (2001). Assuming a typical primary mass of $\sim 3M_\odot$ (the median mass of the red giants in the sample), we find that ~25 per cent (for the uniform distribution) and ~37 per cent (for the Kroupa IMF distribution) of massive binaries $M_{\text{secondary}} > 1M_\odot$ would have a derived minimal mass below $1M_\odot$ due to inclination. We therefore estimate that the real

5, NGC-3247 from Ahumada (2003) and NZ-Zor-1’s mass was taken from NGC-6067 age according to Majaess et al. (2013).
fraction of massive binaries for the period bin $0.5 < P < 5$ yr is $\sim 1.3 \pm 1.6$ larger than the observed definite fraction obtained by our conservative restriction to a minimal mass larger than $1M_\odot$ (due to unknown inclination).

In order to estimate the amount of massive binaries that may have been missed due to a low signal we performed the following conservative Monte Carlo analysis. We examined the peak-to-valley (PTV) RV variations. We divide the whole sample into two distinct populations - systems with observed low PTV $< 10 \text{km/s}$ and high PTV $> 10 \text{km/s}$.

In the high PTV group, where the vast majority of systems are solved, we have 41 definite massive binaries (29 of them in our period range), 46 systems with a solved orbit but a derived minimal mass $< 1M_\odot$ and 23 unsolved systems. We reviewed the data for each of these 23 candidates and found that 13 of them are potential genuine binaries with too little observations to determine the minimal mass and period. Given that about a third of the solved binaries with high PTV have $M_{\text{minimal}} > 1M_\odot$ and $0.5 < P < 5$ yr, we expect $\sim 5$ of these systems to be relevant massive binaries. For each of the systems with PTV $< 10 \text{km/s}$, we estimated the probability $P_{\text{PTV}}$ that a RV curve with a minimal mass of $1M_\odot$ would result with a PTV value which is lower than the one observed due to the limited sampling of the curve. This was done by calculating for each such system, $10^3$ RV synthetic signals at the observed phases by assuming the existence of a massive companion $M_{\text{secondary}} = 1M_\odot$ on an edge-on orbit ($\sin i = 1$) with a period drawn from a uniform distribution in log space in the range $0.5 < P < 5$ yr, eccentricity drawn from a uniform distribution (throwing out systems with periastron $< 0.5\text{AU}$), uniform orientation

$$0 \leq \omega < 2\pi \text{ and initial phase } 0 \leq T < P.$$  
The probability $P_{\text{PTV}}$ has a uniform distribution and an expectation value of $< P_{\text{PTV}} > = 0.5$. In practice, the expectation value is larger due to measurement errors (which tend to increase the PTV). An upper limit for the number of missed systems is thus obtained by $N = 2 \times \sum_i P_{\text{PTV}, i} \sim 17$. Assuming $\sim 15$ missing systems due to inclination, $\sim 5$ missing systems in the high PTV group and $\sim 15$ missing systems in the low PTV group, we obtain an upper limit of $\sim 65$ systems in total or $\sim 8$ per cent of the sample. Assuming only the expected $\sim 20$ missing systems due to unknown inclination, implying $\sim 50$ systems with massive companions in the period range $0.5 < P < 5$ yr, allows a 1$\sigma$ lower limit due to Poisson statistics of about $(50 - \sqrt{50})/797 \approx 0.05$. The observed fraction of systems $29/797 \sim 0.035$ is thus a conservative lower limit.

### Figure 3
The probability that a binary system with a primary $M_{\text{primary}}$ and a secondary $M_{\text{secondary}}$ is sufficiently inclined so that the minimal mass deduced from an RV measurement of the primary is $<1M_\odot$. Different curves show the probability as a function of the secondary mass for different primary masses.

### 4 DISCUSSION
In this paper we analysed previous AO observations of A-type stars by De Rosa et al. (2014) (section § 2) and RV measurements of red-giants in open clusters by Mermilliod et al. (2008) (section § 3) to obtain a robust estimate of the fraction of massive stars $1 < M < 8M_\odot$ that have (lighter) $M > 1M_\odot$ companions in a wide orbit ($P \geq 1$ yr). Assuming that these systems will remain intact when the stars evolve to become WDs within $\leq 10$ Gyr, they will become wide orbit double degenerate systems (WODDs). The results for the two populations are shown in Fig. 4. As can be seen, the binarity fraction per logarithmic period bin is rather constant across 4 orders of magnitude $0.5 < P < 5000$ yr using different techniques. About $\sim 15-20$ per cent of massive stars have such massive companions in this period range with about $\sim 4$ per cent for each dex of period. The samples are likely close to being complete in this range given the high luminosity (for large separations) and large RV signal (for low separations) as demonstrated in sections § 2 and § 3 (except for the $5 < P < 50$ yr bin where we obtain a lower limit for the fraction $\sim 2$ per cent). The upcoming release by GAIA, expected in September 2016, should confirm the results based on the AO observations at large separations with much larger statistics. In particular, by providing parallax and proper motion for the Tycho 2 catalogue, main sequence (MS) stars with $M > 1M_\odot$ should be measured to over 100 pc.

Based on these results we expect that $\sim 15 - 20$ per cent of WDs have wide orbit ($P \geq 1$ yr) companions which are either (lighter) WDs or massive MS stars ($M > 1M_\odot$).  

In order to estimate the fraction of WDs that have a wide orbit WD companion, the fraction of stars with $M > 1M_\odot$ that have already evolved into WDs needs to be estimated. Assuming the age of our galactic disk is $\sim 9.5$ Gyr (Oswalt et al. 1996), a constant star formation rate (SFR), an initial mass function ($\text{IMF}$) of $dn/dm \propto m^{-2.3}$ (Kroupa 2001) and a MS lifetime of $t_{\text{MS}} = 10$ Gyr$(M/M_\odot)^{-1.5}$, we simulate the population of WDs in the galactic disk where for every forming A-type or earlier star ($M > 1.5M_\odot$) we assign a 0.17 chance to be found in a wide orbit with another (lighter)

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6 The ten systems excluded are: NGC-663-319, NGC-2099-12, NGC-2099-255, NGC-6940-188, NGC-2324-2555, NGC-6067-240, NGC-6208-48, NGC-6664-53, NGC-2099-92 and Melotte-71-29.

7 This does not necessarily apply to low mass WDs, $M_{\text{WD}} \leq 0.55M_\odot$ whose progenitors with mass $M \leq 1.5M_\odot$ were not probed by the samples presented here.
Figure 4. The fraction of massive stars that have lighter companions with $M_{\text{secondary}} > 1M_\odot$ as a function of the orbital period. The red solid line and red dashed line represent lower and upper bounds respectively from RV measurements of red giants in open clusters in the logarithmic period bin $0.5 < P < 5$ yr. Blue solid lines with error bars (1σ statistical) represent the fraction obtained from AO measurements of A-type stars in two logarithmic bins in the range $50 < P < 5000$ yr (based on 5 detected systems in each bin). The blue line in the period bin $5 < P < 50$ yr is a rough lower limit (based on the 2 systems detected) in this range which is only partly covered by the AO survey.

MS companion with $M > 1M_\odot$ (independent of the companion’s specific mass). We find that a fraction of $\sim 60$ per cent of the lighter companions in massive binaries in which the primary already evolved to a WD will also evolve to a WD implying that $\sim 10$ per cent of WDs have a wide-orbit WD companion.

These expectations can be directly compared with the statistics of observed companions to WDs. Out of the $\approx 120$ WDs with $M > 0.5M_\odot$ and $D < 20$ pc presented in Holberg et al. (2016) we would expect $\sim 10$ WODDs and $\sim 5$ wide orbit systems with a WD and a MS companion with $M > 1M_\odot$. In the observed sample there are 3 WODDs (WD-0727+482, WD-2226-754 and WD-0747+073) and 4 WD-MS($M > 1M_\odot$) systems (Sirius B, Procyon B, WD-1544-377 and WD-0415-375). The small number of detected WODDs compared to the expectation is unlikely to be due to a statistical fluctuation. This strengthens our previous suspicions that there are missing WDs in multiple systems in the local sample (Ferrario 2012). We expect that about $\sim 10$ WODDs be detected within $20$ pc in the future. In particular, the GAIA astrometric mission should eventually detect most of these missing systems by resolving the systems with large separations $P > 10$ yr and finding astrometric solutions for the systems with close separations $P > 10$ yr. If the fraction of WODDs is established to be much smaller than 10 per cent, this would raise the interesting possibility that many wide massive binaries become unbound before they become WDs.

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Our estimate of the WODD fraction places a tight constraint on the feasibility of the collision model as a primary channel for type Ia supernovae. Following the same assumptions made above and assuming delay time distribution of type Ia SNe of Maoz et al. (2012); Graur & Maoz (2013) we find that $\sim 10$ per cent of WODDs should end up with a collision of the WDs in order to account for the SNe rate. This result can be equivalently obtained by assuming production of 0.1 WDs and 0.001 type Ia SNe per $M_\odot$ of star formation combined with our result that $\sim 10$ per cent of WDs end up in WODDs. This is in tension with the estimate that only a few percent of triple systems with WODDs having the right hierarchy (Katz & Dong 2012) lead to a collision. This suggests that in order for the collision model to work, either the majority of WODDs have a relevant tertiary (leaving a modest discrepancy of order 2) or that other effects such as higher multiplicity (Pejcha et al. 2013) or passing stars (Antognini & Thompson 2016) substantially increase the chance for collisions in some of the systems.

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