Radial velocities and binarity of southern SIM grid stars

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ABSTRACT
We present analysis of precision radial velocities (RV) of 1134 mostly red giant stars in the southern sky, selected as candidate astrometric grid objects for the Space Interferometry Mission (SIM). Only a few (typically, two or three) spectroscopic observations per star have been collected, with the main goal of screening binary systems. The estimated rate of spectroscopic binarity in this sample of red giants is 32 per cent at the 0.95 confidence level, and 46 per cent at the 0.75 confidence. The true binarity rate is likely to be higher, because our method is not quite sensitive to very wide binaries and low-mass companions. The estimated lower and upper bounds of stellar RV jitter for the entire sample are 24 and 51 m s\(^{-1}\), respectively; the adopted mean value is 37 m s\(^{-1}\). A few objects of interest are identified with large variations of RV, implying abnormally high mass ratios.

Key words: binaries: spectroscopic – stars: kinematics and dynamics.

1 INTRODUCTION
Space Interferometry Mission (SIM) was designed to perform global and narrow-angle astrometry at an unprecedented precision level of 1–10 \(\mu\)as per single measurement. At the time of its termination by NASA (following an explicitly negative assessment by the National Academy of Science in the Astro2010 Decadal Survey) SIM was in an advanced Phase B, having passed all eight technology development milestones. One of the ongoing Phase B studies was aiming at constructing a uniform, all-sky grid of reference stars, which would serve as an important stepping stone towards generating a global reference frame at an \(\approx\)4 \(\mu\)as level (Unwin et al. 2008). SIM would spend a considerable fraction of its operational lifetime observing some 1300 grid stars in the wide-angle regime. The grid was needed to construct a rigid global reference frame from essentially differential path delay measurements of objects within a 15\(_\circ\)-diameter field of regard (Makarov \& Milman 2005). Establishing a set of verified, astrometrically stable grid stars was crucial for the success of the global astrometry mission. In particular, a significant fraction of binary systems among the culled grid objects could jeopardize the project.

Grid star candidates were selected by an elaborate system of criteria, deemed to maximize the rate of stable, single stars. A detailed discussion of the criteria is rather technical and is outside the scope of this paper. Candidate grid stars were selected among presumably early K and clump giants, with estimated distances between 500 and 1000 pc. Preference was given to candidates with small to moderate proper motions. The latter criterion was supposed to reduce the risk of selecting nearby red dwarfs, since neither spectroscopic luminosity class nor parallaxes were available for these 10–11 mag stars. The candidates were found mostly in the Tycho-2 catalogue (Høg et al. 2008), avoiding the objects listed in the Tycho Double Star Catalogue (Fabricius et al. 2002), and from the Guide Star catalogue. Most of the sample stars have \(B - V\) colours between 1.0 and 1.3 mag. All stars have declinations south of \(-21^\circ\).

The SIM project office organized a large-scale observational campaign to screen spectroscopic binaries in both celestial hemispheres. High-precision radial velocity (RV) observations of some 3500 grid candidates were to be collected by three teams through a competitive contract on medium-class telescopes. One of the teams, led by Swiss astronomers Didier Queloz and Damien Segransan, produced the largest and most precise set of data spanning 753 days. The team used the 1.2 m Euler telescope in ESO La Silla Observatory, Chile, equipped with the CORALIE spectrograph. The set-up of the instrument and the observing technique are similar to those used for the exoplanet search programme (Queloz et al. 2000). Additional information on the calibration and data reduction techniques can be found in (Baranne et al. 1996).

2 RV, ERRORS AND BINARITY
The data set used in this paper is structured as shown in Table 1. A few lines of data are given for each of the 1134 observed stars. The first line is a header, consisting of the star’s name, equatorial coordinates (right ascension and declination) on J2000, number of RV measurements \(n_{\text{obs}}\), derived mean RV in km s\(^{-1}\) and its uncertainty (including the estimated stellar jitter) in km s\(^{-1}\), binarity confidence, binary flag (0 for non-binary, 1 for binary) with 0.75

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The residuals are then used to compute the weighted mean RV, which is followed by the specified number of individual RV measurement lines. Each line contains the Julian date of observation, observed RV in \( \text{km s}^{-1} \), and the formal observational error in \( \text{m s}^{-1} \). The latter is the estimated instrument error only, and as such, it does not include any uncertainty associated with the physical nature of the object. A notable uncertainty associated with the physical nature of the object. A physical jitter, but this assumption can only be verified by simultaneous, high-accuracy RV and photometric measurements at high cadence.

Table 1. RV data for 1334 SIM grid stars.

<table>
<thead>
<tr>
<th>Star Identification</th>
<th>RV (\text{km s}^{-1})</th>
<th>RV Uncertainty (\text{m s}^{-1})</th>
<th>( n )</th>
<th>( \chi^2 )</th>
<th>CDF</th>
<th>Binary Flag</th>
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</thead>
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<td>35.074 871</td>
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</tbody>
</table>

Notes. The entire catalogue is available online. The columns in a header line are (1) star identification, mostly TYC, which are consistent with the SIMBAD search engine; (2) right ascension at J2000 in degrees; (3) declination at J2000 in degrees; (4) number of RV measurements; (5) mean RV in \( \text{km s}^{-1} \); (6) mean RV uncertainty including the estimated stellar jitter in \( \text{km s}^{-1} \); (7) binarity confidence; (8) binary flag (0 for non-binary, 1 for binary) with 0.75 confidence; and (8) binary flag with 0.95 confidence. The columns in a data line are: (1) Julian date of observation; (2) observed RV in \( \text{km s}^{-1} \); and (3) the formal observational error in \( \text{m s}^{-1} \).

If we knew which of the observed stars are spectroscopically single, we could easily estimate the sample-mean jitter. The mean jitter is quadratically added to the instrumental error for each observation, and the median \( \chi^2 \) over the sample of single stars should be close to the argument of CDF at 0.5. In other words, half of the single stars should have \( p \)-values smaller than 0.5. But it is not known a priori which stars are single, therefore, we can estimate only robust bounds for the jitter component. The upper bound is derived from the assumption that the observed scatter is only due to observational error and jitter, i.e. all the stars in the sample are non-binary. The level of jitter is adjusted until the median \( \chi^2 \) is equal to the expected value \( k(1 - 2/(9k))^3 \) (Wilson & Hilferty 1931). The upper bound for the mean jitter thus estimated is 51 m s\(^{-1}\). The actual value is certainly smaller, because a significant fraction of the sample are strongly perturbed by binarity. The lower bound for jitter comes from the assumption that only the higher half of sample values \( \chi^2 \) are affected by spectroscopic binarity. The jitter level is adjusted until the median \( \chi^2 \) of the lower half of the sample distribution reaches the expected value \( k(1 - 2/(9k))^3 \). The lower bound comes up to 24 m s\(^{-1}\). We adopt the mean of the two bounds, 37 m s\(^{-1}\), as the average jitter dispersion for the sample. This value is likely to be slightly overestimated because, as we will see shortly, the rate of detectable binaries seems to be closer to 0.5 than to 0.
With this amount of jitter quadratically added to the formal instrument errors, the resulting distribution of confidence levels is shown in Fig. 1. We note that the distribution of confidence levels is quite flat everywhere except the highest bin. The flatness of this distribution is a significant result in itself, pertaining to the nature of binary systems with red giant primaries. With 2 degrees of freedom, the $\chi^2$ reaches 10 for the corresponding CDF value of $\approx 0.993$. The mass of companion in a 1-yr orbit corresponding to this detectable signal is of the order of 0.005 $M_{\odot}$. In principle, even giant exoplanets can be detected with three observations. The range of confidence levels between 0.993 and 0.9999 corresponds to $\sim$1000 $M_{\odot}$ mass range, and this data should be sensitive to super-Jupiters and brown dwarf companions in 1-yr orbits. The absence of significant excess at these confidence levels seems to confirm the 'brown dwarf desert' phenomenon, i.e. the paucity of substellar-mass secondary companions in binary systems. However, when the jitter is set at the lower bound level of our accepted jitter value (37 m s$^{-1}$) for the lower confidence threshold 0.75. As previously discussed, our accepted jitter value (37 m s$^{-1}$) may be overestimated. The true binary rate is likely between 37 and 46 per cent. If we set the jitter component at the lower bound of 24 m s$^{-1}$, the estimated rate of binaries comes up to 41 per cent at 0.95 confidence. This number may include the contribution of substellar-mass companions.

3 OBJECTS OF NOTE
A few stars in the sample have unusually large RV variation, implying exceptionally high mass ratios or very short orbital periods, or both. We select two such objects, which deserve a careful follow-up investigation.

TYC 6948-00350-1 = HD 206092 was observed with a total RV range of 266 km s$^{-1}$. This G9 III star has been identified by Kiraga (2012) as rotationally variable with an astonishing period of 2.1876 d and a line broadening parameter $v \sin i$ of 80 km s$^{-1}$. Now it is also detected as a spectroscopic binary with an RV semi-amplitude of at least 133 km s$^{-1}$. Assuming that the primary star is synchronized, and the rotation period equals the orbital period, the mass ratio for this system should be above 1, or the eccentricity should be high. The latter option is not feasible in the light of previous studies of rotational velocities of red giants in binary systems (Massarotti et al. 2008), which found that all binaries with periods shorter than 20 d are circularized. We attempted to fold the available RV measurements with the rotational period, but failed to obtain a clear phase curve. Follow-up photometric and spectroscopic observations are needed to reveal the nature of this enigmatic object.

TYC 7381-00433-1 = HD 318347 has an RV range of at least 212 km s$^{-1}$. Little is known about this star. Surprisingly though, it is listed in SIMBAD as O$^*$ type with emission lines, that is, a very hot and massive star. However, it is quite red with a $B - V = 0.92$ determined by Drilling (1991). We surmise this binary star may include a regular red giant accompanied by a post-AGB star or some other rare type of object on a short-period orbit.

4 DISCUSSION
Our estimate of multiplicity fraction for 1333 randomly selected, field red giant stars is close to the more accurately known rate for nearby solar-type stars, 46 ± 2 per cent (Raghavan et al. 2010). Our best estimate is 41 per cent, which may or may not include companions of substellar mass, depending on the actual level of stellar RV jitter and its distribution. The method of binarity detection employed in this paper is not sensitive to binaries with orbital periods longer than several years, possibly lowering this estimate by several per cent. The wider separation pairs are to be detected by direct imaging (Tokovinin et al. 2012) or astrometric techniques (Makarov, Zacharias & Hennessy 2008). They may contribute a few more per cent to the all-inclusive multiplicity fraction, although the wide and common proper motion companions are often found in hierarchical multiple systems (Makarov & Eggleton 2009). On the other hand, dwarfs more massive than the Sun, which are more likely to be the progenitors of the present-day K giants, have a slightly higher binarity rate than their subsolar counterparts (Duchêne & Kraus 2013). The overarching conclusion is that there seems to be no significant difference in the incidence of binarity among main-sequence dwarfs and field red giants.

Our results are consistent with other observational data for field red giants. Setiawan et al. (2004) collected and analysed RV data for 77 G and K giants and detected a 20 per cent multiplicity rate, despite the preliminary binarity screening. The RV jitter for those bluer and less luminous giants not detected as binary was constrained to $< 60$ m s$^{-1}$. Based on the much larger sample and more observations, we are able to drastically improve these estimates.

ACKNOWLEDGEMENTS
Part of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Figure 1. Histogram of spectroscopic binarity confidence levels for 1333 grid stars with more than 1 RV measurements.

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REFERENCES
SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. RV data for 1334 SIM grid stars.

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