A Strategy for Identifying the Grid Stars for the Space Interferometry Mission (*SIM*)

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ABSTRACT

We present a strategy to identify several thousand stars that are astrometrically stable at the micro-arcsecond level for use in the *SIM* (Space Interferometry Mission) astrometric grid. The requirements on the grid stars make this a rather challenging task. Taking a variety of considerations into account we argue for K giants as the best type of stars for the grid, mainly because they can be located at much larger distances than any other type of star due to their intrinsic brightness. We show that it is possible to identify suitable candidate grid K giants from existing astrometric catalogs. However, double stars have to be eliminated from these candidate grid samples, since they generally produce much larger astrometric jitter than tolerable for the grid. The most efficient way to achieve this is probably by means of a radial velocity survey. To demonstrate the feasibility of this approach, we repeatedly measured the radial velocities for a pre-selected sample of 86 nearby *Hipparcos* K giants with precisions of 5–8 $\mathrm{m\,s^{-1}}$. The distribution of the intrinsic radial velocity variations for the bona-fide single K giants shows a maximum around 20 $\mathrm{m\,s^{-1}}$, which is small enough not to severely affect the identification of stellar companions around other K giants. We use the results of our observations as input parameters for Monte-Carlo simulations on the possible design of a radial velocity survey of all grid stars. Our favored scenario would result in a grid which consists to 68% of true single stars and to 32% of double or multiple stars with periods mostly larger than 200 years, but only 3.6% of all grid stars would display astrometric jitter larger than 1 μas. This contamination level is probably tolerable.

Subject headings: astrometry — binaries: general — reference systems — stars: oscillations — techniques: radial velocities

1. Introduction

The Space Interferometry Mission (*SIM*, see e. g. NASA 1999), which is currently scheduled for launch around 2008/2009 and one of the next major steps in NASA's Origins Program (Thronson 1997), is designed to perform astrometry at the $4\,\mu$as level in its wide-angle mode and at the $1\,\mu$as level in its narrow-angle mode. The instrument is a Michelson Interferometer with a 10 m baseline, operating in the visible.

The detection of extrasolar planets via the astrometric wobble they induce in their parent stars is one of the main scientific goals of the *SIM* mission. The astrometric accuracy at the end of a 5 year mission will allow for the detection of Jupiter-like planets at distances up to ≈ 1 kpc (the astrometric signature of Jupiter at 1 kpc is $10\,\mu$as) and of planets of a few Earth masses around the most nearby stars.

The unprecedented accuracy of *SIM*, which is two to three orders of magnitude better than what was achieved with the recent *Hipparcos* astrometric satellite (ESA 1997), strongly depends on the astrometric stability of its grid objects. The grid consists of several thousand stars distributed uniformly over the sky, with the exact number depending on the final optical design of the *SIM* instrument. Dedicated grid campaigns will be carried out several times a year, with a total of about 110 visits for each star. The grid then serves as a reference frame to which the individual science observations can be tied. In addition to enabling wide-angle astrometry the grid also will lead to improvements in the International Celestial Reference Frame, ICRF (see e.g. Gaume et al. 1999 or the review by Johnston & de Vegt 1999).

A few radio-loud quasars will be included in the grid to establish a direct link between the optical reference frame defined by the *SIM* astrometric grid and the radio-based ICRF. The inclusion of a few quasars in the grid also helps to eliminate possible spurious rotation of the *SIM* reference frame.

Finding well-suited grid stars is by no means an easy task. Improving any measurement accuracy by several orders of magnitude always implies the chance (and risk!) of finding something new and unexpected. The aim of this study is to present a strategy that can minimize any such unwanted surprises for the *SIM* astrometric grid stars.

The importance of a low contamination level of the grid sample with astrometrically unstable stars is illustrated in Table 1, where we calculated the percentages of usable *SIM* observations for various contamination levels from basic statistics. As a minimum four good grid stars are required for every science observation to solve for the baseline, but some redundancy would be highly desirable. For an assumed contamination level of 5% of the grid with unusable stars and six scheduled grid star observations statistically 99.8% of all science observations could be used. However, with a grid star failure rate of 20% the fraction of usable science observations will decrease to only 90%, wasting valuable mission time. In order to increase the success rate to 99%, eight instead of six grid stars would have to be observed along with every science observation. At least for bright science targets this would add significant overhead compared to the integration time spent for the actual target and would thus significantly lower the overall number of stars that could be observed with *SIM*. Instead, we propose an intense ground campaign to eliminate astrometrically unstable stars from the grid.

This paper is organized as follows. After arguing for K giants as the type of stars which is best suited for use with the *SIM* grid in Section 2, we define a nearby proxy sample of *Hipparcos* K giants and present the first results of a precise radial velocity study in Section 3. In Section 4 we outline a strategy to identify several thousand well-suited grid stars within the next few years. Finally we discuss our results in Section 5 and provide a short summary in Section 6.

2. Which Types of Stars would be Good Grid Stars?

The concept of the *SIM* Astrometric Grid is described e.g. in the *SIM* Book (NASA 1999), Boden (1999) or the *SIM* website[1]. In addition to the dedicated grid campaigns a minimum of four grid stars will be observed along with each science target to solve for the spacecraft orientation. Depending on the size of *SIM*'s Field of Regard (FOR) this gives a minimum number of grid stars required to cover the sky. However, a larger number of stars per tile (corresponding in size to the

[1] http://sim.jpl.nasa.gov/

Table 1
Percentages of usable *SIM* observations

no. of grid stars per science obs.	contamination level 5%	10%	20%	50%
4	81	66	41	6
5	97.7	92	74	19
6	99.8	98	90	34
7	99.98	99.7	97	50
8	99.999	99.96	99	64

FOR) is highly desirable, for redundancy as well as for attrition reasons among grid stars. The current grid star design anticipates twelve stars for each tile and a FOR of either 15 or 20 degrees, resulting in a total of approximately 3000 or 1500 grid stars, respectively.

A larger number of grid stars has the advantage that the separations between science targets and grid stars are smaller, which increases the astrometric accuracy. Furthermore, if it turns out during the mission that observations in a specific tile are compromised because not enough grid stars fulfill the requirements on astrometric stability, it does not have such a high impact as in the case with only half as many tiles and grid stars. On the other hand, however, a larger number of qualifying stars is more difficult to find and requires a larger amount of observing resources from the ground, before the mission, as well as longer *SIM* grid campaigns.

In any case, the grid stars have to be distributed uniformly over the sky. This requirement, among other shortcomings like the difficulty to measure precise radial velocities for fast rotating stars, precludes O or B stars from being grid stars, because these are concentrated in the spiral arms of the galactic disk. Furthermore, the grid stars should in general not be fainter than about 12 mag, because otherwise the fraction of *SIM* observing time dedicated to the grid instead of actual science observations would become too large.

The most important and most challenging requirement however is the astrometric stability of the photocenter of the grid objects to within a few microarcseconds.

Most double[2] stars are therefore unacceptable as grid stars, because the orbital motion imposes too many uncertainties in the position and velocity model for a grid star; the residual non-modeled uncertainties in the positions of the stars, the so-called astrometric jitter, would be much larger than a few microarcseconds. Even planets can impose problems, but since the astrometric signature scales with the inverse of the distance one can get rid of part of the problem by choosing rather distant grid stars. Note that parallactic and linear motions of the grid stars do not impose any problems since parallax and proper motions can be determined from the *SIM* observations with the required precision and need not be known before the mission.

Since the apparent magnitude for grid stars is limited this calls for intrinsically bright stars like K giants. In terms of brightness M giants would work even better, but most of them are highly variable and therefore not very well suited as grid stars. A 12 mag K giant would typically be located at about 2 kpc, assuming an absolute magnitude M_V of +0.5 mag for solar metallicity. Metal-weak halo K giants are up to 2 mag brighter, which places them at distances up to 5 kpc. The astrometric signature of a Jupiter-like companion, assuming one solar mass for the parental star, would be 5 μas peak-to-peak at 2 kpc and 2 μas peak-to-peak at 5 kpc.

This level is still at the higher end of what would be acceptable for *SIM*. While a reasonable strategy exists on how to clean a candidate grid star sample from unwanted multiple systems,

[2]speaking of double or binary stars in this paper we always mean to include triple, quadruple and all other multiple stars

there is no way to assure the absence of planets for such a large sample of stars with the instruments on hand at present. Brown Dwarfs however are not a big concern, see Section 2.1.

K giants are known to be photospherically active. This leads to intrinsically variable radial velocities, which could complicate the identification of binaries among a sample of K giants. Sections 3 and 4 deal with this problem and show that this is not a severe complication. Another related effect is the photocenter shift induced by starspots. However, most starspots are not large and cool enough to produce measurable photocenter shifts at distances of several kpc.

There is no reasonable alternative to using K giants as grid objects. Bright G dwarfs, which had also been suggested as grid stars in earlier phases of the project, would be advantageous in terms of already available information as well as brightness since that they could be easily observed at moderately sized telescopes. Most stellar companions could probably be identified using already available data, and one might even be able to exclude giant Jupiters as companions by selecting the rejects of current planet searches. However, given the magnitude limit of 12 mag for grid stars, G dwarfs would be located at distances not larger than 300 pc. The astrometric signature of a Jupiter at that distance would be more than 30 μas, clearly much larger than acceptable. For brighter and thus closer G dwarfs even Saturn-mass planets would generate detectable astrometric signals. Furthermore, we already know now that planetary companions to solar-like stars are numerous; these are the stars monitored by the radial velocity planet search programs (see e.g. Mayor et al. 1999; Marcy et al. 2000).

2.1. Brown Dwarf Desert

We have plotted the number of companions found in the planet and Brown Dwarf mass ranges normalized by the number of stars surveyed for all radial velocity planet searches that have found planets or Brown Dwarf companions so far (Fig. 1). Note that the surveys are still very incomplete in the planet mass range; planet identifications just continue to drop out of these surveys with time. On the other hand, however, the surveys are very sensitive to companions in the Brown Dwarf mass range, yet very few — if any after elimination of the sin i uncertainty — have been found. It is unlikely that a significant number of planetary companions with M$\cdot$sin i below 10 M_J will be shifted to the Brown Dwarf regime, since low values for sin i are really rare.

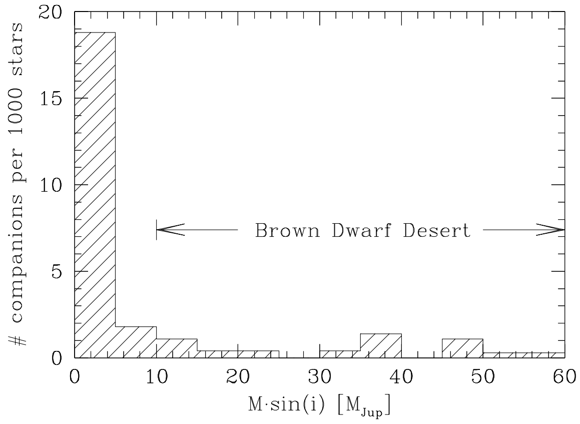

Fig. 1.— Histogram of substellar companions that have been found by radial velocity searches, normalized by the number of stars surveyed. Included are the results from planet searches using the Hamilton Spectrograph at Lick Observatory, HIRES at Keck, the Coravel, Elodie and Coralie spectrographs at Observatoire de Haute-Provence and at La Silla, CES at La Silla, the AFOE spectrograph at Whipple Observatory, and at the Smithsonian Astrophysical Observatory. The lack of systems in the Brown Dwarf mass range is clearly evident, especially since the radial velocity surveys are more sensitive to higher masses and the diagram is fairly incomplete towards lower masses. The elimination of the sin i uncertainty is not likely to change the appearance of this diagram significantly.

However, radial velocity surveys are much more sensitive towards smaller separations, and very little is known so far about Jupiter mass planets beyond about 5 AU. Brown Dwarfs would still produce a detectable radial velocity signal at separations up to about 30–50 AU, or periods of about 200 years (see Fig. 2). Beyond, the annual changes in the radial velocities would be too small to be recognized over timescales of a few years. Astrometric detections probe a different parameter space since the astrometric signal is larger for larger separations, although for astrometric detections the large involved periods are just as limiting as they are for the radial velocity detections. Other techniques like direct imaging or the 2MASS Survey have revealed only very few Brown Dwarf companions so far (Oppenheimer 1998; Rebolo et al. 1998; Burgasser et al. 2000). Halbwachs et al. (2000) derived astrometric orbits for eleven spectroscopic binaries with Brown Dwarf Candidates from *Hipparcos* data and concluded that there is a real minimum in the mass distribution of companions to solar-type stars.

Thus it seems to be justified to speak of a Brown Dwarf Desert (Marcy & Butler 2000) — while numerous isolated Brown Dwarfs exist, very few seem to be companions to solar-like stars. Since these solar-type stars are the precursors of K giants, this finding should equally well hold true for them. So if we are able to sieve a sample of grid star candidates for the stellar companions, we can take advantage of the Brown Dwarf Desert. The only companions that are left in the sample are planetary companions, and their disturbing effects can be minimized by placing the stars at the largest possible distances.

2.2. How to Identify Suitable K Giants

The most precise and comprehensive astrometric catalogs available today are the Hipparcos and Tycho-2 Catalogues (ESA 1997; Høg et al. 2000), which makes them a natural first choice when searching for astrometric reference stars. The Hipparcos Catalogue contains about 120 000 stars with an accuracy of ≈1 mas for positions and parallaxes and ≈1 mas·yr^{-1} for proper motions. It also provides a wealth of supplementary information like spectral types, variability or duplicity information, which allows for a thorough preselection of suitable reference stars. Comparison of the instantaneous *Hipparcos* proper motion with proper motions derived from larger epoch differences, as provided e.g. by ACT (Urban et al. 1997) or TRC (Høg et al. 1998), can reveal astrometric binaries (cf. Wielen et al. 1999). The parallaxes can be used to distinguish K giants from K dwarfs.

Exploiting all the information available, we are left with a sample of 11 813 candidate K giant grid stars out of a total of 29 466 K giants present in the Hipparcos Catalogue. The full set of applied selection criteria is given in the appendix (see also Frink et al. 1999). The selection criteria work somewhat better for brighter stars, for which on average more information is available than for the fainter part of the sample: among the stars brighter than 6 mag 87 % have been rejected as possible grid stars, while the average percentage of rejected grid stars is 60 % for the whole sample. However, since we wanted to demonstrate the possibility to find grid stars which fulfill the requirements of the *SIM* grid, we concentrated on the very best grid candidates and chose rather strict selection criteria, so that it is likely that also a number of in fact well-suited reference stars got rejected.

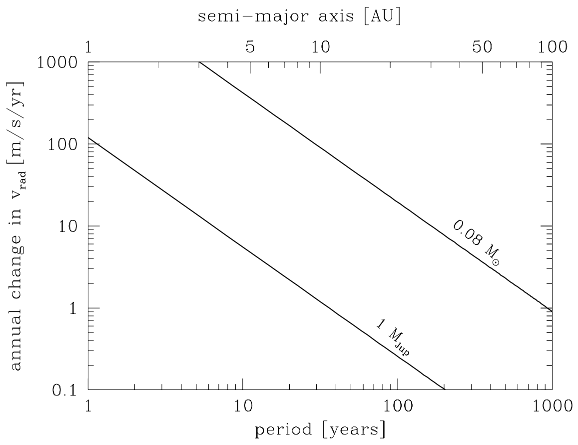

Fig. 2.— Approximate trends that would be observable in the radial velocities of solar-type stars of 1 M$_\odot$ if they had a companion with masses of 1 M$_J$ and 0.08 M$_\odot$, respectively. Inclinations of 90° and circular orbits have been assumed in calculating the annual radial velocity changes. The semi-major axis scale at the top corresponds to the case of a 1 M$_J$ companion; for the companion of 0.08 M$_\odot$ it would have to be increased by about 5% to match the period scale at the bottom. Current radial velocity surveys would probably be able to detect Brown Dwarfs up to separations of 30–50 AU, corresponding to periods up to about 200 years.

The use of the sample defined in this way is twofold:

(1) The brighter end of the sample can be used as a proxy sample to study the properties of K giants as grid stars in some detail. 177 *Hipparcos* K giants brighter than 6 mag were selected as proxies for possible grid stars. We started to monitor

the intrinsic radial velocity variations in this sample of bona-fide single stars at Lick Observatory, and the first results of these observations are presented in the next section.

(2) On the other hand, the faint end of the sample contains actually good astrometric reference stars at distances as needed for the *SIM* grid, i.e. larger than ≈ 1–2 kpc. We computed photometric distances for these stars using the spectral type given in Hipparcos under the assumption of solar metallicity. For metal-weak K giants these distances are a lower limit only, whereas for stars with a considerable amount of extinction along the line of sight the computed distances will be too large. However, the accuracy is good enough to sort out most K giants which are not located at the required minimum distance, and we ended up with a sample of only 45 *Hipparcos* K giants with computed distances larger than 1 kpc. These could be actually good grid candidates, provided that the radial velocities show no variability.

It is obvious that not enough *SIM* grid stars can be found in the Hipparcos Catalogue; although the magnitude limit is 12.4 mag, it is complete only to 7.3–9 mag, depending on position on the sky. Recently, the Tycho-2 Catalogue (Høg et al. 2000) has been published, which contains 2.5 million stars with a completeness level of 90 % at 11.5 mag. It is based on the same observational material as the Tycho-1 Catalogue, supplemented with 144 ground based astrometric catalogues. Furthermore, a more rigorous reduction has been applied for Tycho-2, leading to astrometric accuracies of 60 mas for positions and 2.5 mas$\cdot$yr^{-1} for proper motions. Color information in the Tycho B_T and V_T passbands allows for the identification of K stars, while the proper motions can be used to distinguish between K giants and K dwarfs in a statistical sense. Comparison with the Hipparcos data showed that less than 10 % of either K dwarfs or K giants would be misclassified because of extraordinarily small or large proper motions, respectively. Since there are about 10 times as many K giants as K dwarfs in the magnitude-limited samples considered here, this results in a very small contamination fraction of a K giant sample with K dwarfs of about 1 %.

Applying a similar set of selection criteria as for the *Hipparcos* stars (see appendix), we were able to identify a sample of $\approx$8000 K giants from Tycho-2 with computed distances larger than 1.5 kpc, see also Frink et al. (2000). This sample of promising *SIM* grid stars could be used as a starting point for a radial velocity survey which then has to identify the truly single stars among the grid candidates.

A completely different approach is followed by Majewski, Patterson and co-workers (Patterson et al. 1999). They are currently conducting a patchy all-sky survey at Las Campanas Observatory, aimed at identifying distant Halo K giants for the *SIM* grid. This is accomplished by a photometric survey with a special set of filters, followed by a spectroscopic verification of the K giant nature. Most of the stars are metal-weak K giants around 12 mag.

These large distances make the sample of stars very well suited for the *SIM* grid; at least in terms of distances and corresponding anticipated astrometric jitter it is superior to the Tycho-2 sample. However, no variability or duplicity information whatsoever is available for the Halo K giant sample, and it will probably take more observational effort from the ground to clean this sample from unwanted double and multiple stars. It would be ideal if it turned out that there was a considerable overlap between the Halo K giant and the Tycho-2 sample, combining the advantages of both stellar samples.

3. A Nearby Proxy Sample

3.1. Observational Results

In order to demonstrate the feasibility of our approach to effectively sort out the double stars from a sample of candidate K giant grid stars we started to measure precise radial velocities for a number of stars in the nearby *Hipparcos* sample defined in the last section. The observations were carried out with the 0.6 m Coudé Auxiliary Telescope (CAT) at Lick Observatory using the Hamilton Echelle Spectrograph in conjunction with the Iodine Cell. The spectra were reduced in the same way as described in Butler et al. (1996), which has been proven to yield accuracies up to 3 m s^{-1}. Exposure times are up to half an hour for 6 mag stars, which results in a typical signal-to-noise ratio of 100 (not lower than about 80, in a few cases as high as 150 or even 200).

We started the monitoring in June 1999 and typically observed for five consecutive nights every

TABLE 2

INTRINSIC RADIAL VELOCITY DISPERSIONS FOR HIPPARCOS K GIANTS IN OUR PROXY SAMPLE

HIP no.	n_{obs}	Δv_{rad} [m s^{-1}]	$\sigma_{v_{rad}}$ [m s^{-1}]	HIP no.	n_{obs}	Δv_{rad} [m s^{-1}]	$\sigma_{v_{rad}}$ [m s^{-1}]	HIP no.	n_{obs}	Δv_{rad} [m s^{-1}]	$\sigma_{v_{rad}}$ [m s^{-1}]
379	5	7.0	36.3	47959	3	4.3	42.8	84950	6	5.0	145.2
2497	6	7.1	29.9	50027	4	6.7	11.6	85139	7	9.0	57.8
6732	7	5.9	30.8	50336	3	5.4	68.4	85888	6	6.3	11.8
9110[a]	4	4.9	137.1	53261	4	4.7	80.2	88636	6	5.9	30.3
11432	8	8.0	18.7	53316	4	6.2	9.6	88684	6	5.6	11.1
13905	7	6.1	23.0	53781	4	5.1	184.4	88839	7	6.1	27.9
15861	5	5.1	370.9	55086	4	5.6	24.9	90067	7	5.1	40.8
19011	8	7.3	23.3	55716	4	4.3	67.5	91004	6	7.2	250.5
19388	8	6.5	14.3	58181	5	6.9	13.4	92747	7	7.9	442.4
22860	7	7.5	12.1	59847	5	8.0	0.0[b]	93026	6	...	...
30457	6	5.7	21.6	61420[c]	3	...	...	96459	8	6.0	4.3
30720	3	2.0	7.4	61571	5	6.4	21.1	101986	8	6.5	52.8
32814	3	4.0	19.9	64078	5	9.3	27.2	105497	8	5.9	21.4
33914	3	3.8	1.2	64823	4	4.7	13.4	108691	8	6.5	27.3
34033	4	4.7	25.7	65323	4	6.0	84.0	109023	7	5.8	20.2
34387	3	3.5	12.9	72210	4	6.1	26.5	109068	8	4.2	27.3
35907	3	2.9	50.4	73133	4	5.6	63.8	109602	7	6.1	30.4
36388	3	3.7	39.4	74239	3	9.7	29.8	110986	5	5.4	91.8
36616	3	2.7	90.5	74732	4	4.2	17.5	111944	6	3.6	39.7
36848	3	5.2	22.7	75730	3	2.8	58.4	112067	6	8.5	18.6
38253	3	4.3	164.6	75944	4	6.6	28.0	113084	6	6.2	21.0
38375	3	4.1	4.2	78132	4	4.5	7.7	113562	6	8.0	218.7
39079	4	4.8	28.2	78442	4	5.0	11.0	113622	6	5.3	18.2
39177	3	4.6	89.3	79195[d]	3	3.0	2179.9	113686	6	7.7	35.7
41909	3	2.9	13.0	79540	7	6.0	31.9	113864	7	5.3	22.7
43923	3	3.4	4.6	80693	7	5.2	64.2	114449	6	5.9	14.8
44356	4	7.1	46.0	81660	6	4.7	14.4	117567	6	6.6	61.4
46982	4	7.9	18.6	83254	7	6.4	100.5	117756	5	6.5	8.8
47189	3	4.3	136.5	84671	6	5.0	45.2				

[a] SB: Gordon 1946; Irwin 1952

[b] observed velocity dispersion is 7.4 m s^{-1}, smaller than the mean error of 8.0 m s^{-1}

[c] SB: Griffin & Eitter 1992

[d] SB: Ginestet et al. 1985

NOTE.—Given are the number of observations for each star, the mean measurement error of the radial velocities, and the intrinsic dispersion. The observed dispersion is the quadratic sum of the last two columns. For stars with only three observations, the measurement errors are somewhat optimistic and will get readjusted once more observations are available for them. For two of the stars it was not possible to calculate the radial velocities, i.e. the fit of Doppler shifted template star spectrum plus iodine did not yield reasonable fits to the individual iodine star spectra. However, this only happens for very large Doppler shifts.

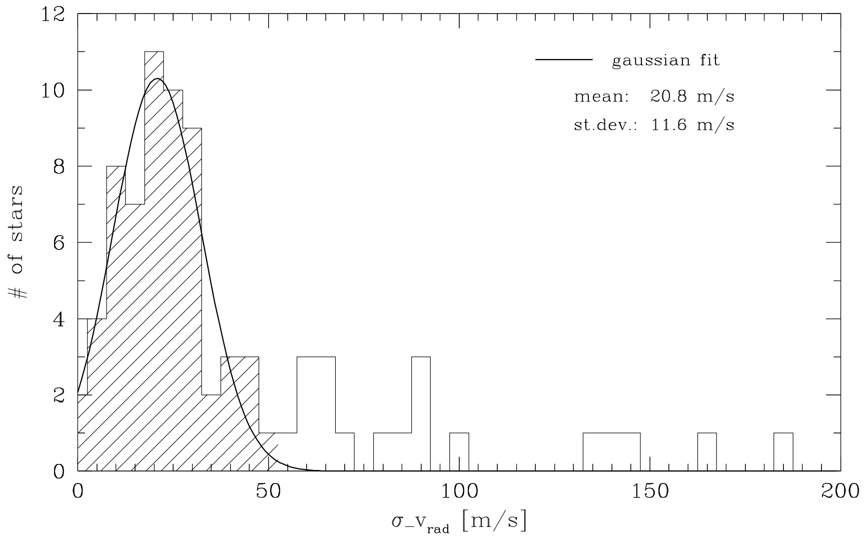

Fig. 3.— Observed intrinsic radial velocity dispersions in our proxy sample of 86 nearby *Hipparcos* K giants as listed in Table 2 (histogram). Five stars with dispersion larger than $200\,\mathrm{m\,s^{-1}}$ are not shown. The solid line is a gaussian fit to the distribution of dispersions smaller than $50\,\mathrm{m\,s^{-1}}$ only (hatched part of the histogram) and reveals a maximum around $20\,\mathrm{m\,s^{-1}}$.

month, so that we are able to probe the intrinsic radial velocity variations on timescales from days up to one year so far. Altogether there are 177 *Hipparcos* K giants brighter than 6 mag that passed our selection process, and 139 of them are accessible from Lick Observatory ($-30° \leq \delta \leq +68°$). Out of these 139 K giants we chose 86 to comprise our proxy sample, including all stars brighter than 5.5 mag. Between 5.5 mag and 6 mag we chose the ones which were most convenient to observe, i.e. according to position on the sky which should not have introduced any biases.

For all stars in our proxy sample we have at least three (typically five or six) observations plus template so far. Typical examples are shown in Fig. 4, and all resulting intrinsic radial velocity dispersions are listed in Table 2.

The first thing to note is that there are still a few spectroscopic binaries present in our sample, which was not obvious from the data given in the Hipparcos Catalogue. Most of them are known spectroscopic binaries, but one or two could be new ones. However, all of them could easily be identified with only two or three observations. Discarding these spectroscopic binaries from our sample, the distribution of intrinsic radial velocity variations shows a peak around $20\ \mathrm{m\,s^{-1}}$ (Fig. 3). The distribution can be fitted by a gaussian with a mean of $20.8\,\mathrm{m\,s^{-1}}$ and a standard deviation of $11.6\,\mathrm{m\,s^{-1}}$. This overall low level of radial velocity variability is remarkable, since it is known from intensive monitoring of a few bright K giants that they can display radial velocity amplitudes of several $100\ \mathrm{m\,s^{-1}}$.

There is a trend with color in the observed radial velocity dispersions in the sense that the redder K giants show larger variations (Fig. 5). This is not too surprising, since these late K giants are located adjacent to the highly variable M giants in the Hertzsprung-Russell diagram. For the selection of the candidate grid stars it might therefore be best to apply a certain color cutoff around $B-V = 1.2\,\mathrm{mag}$.

3.2. Comparison with other studies

The first and best studied K giant with known radial velocity variability is probably Arcturus (α Boo). It was shown to have several short-term periods of the order of a few days by Smith et al. (1987) and Hatzes & Cochran (1994a), as well as a long-term period of 233 days with a radial velocity amplitude of $500\,\mathrm{m\,s^{-1}}$ (Hatzes & Cochran 1993).

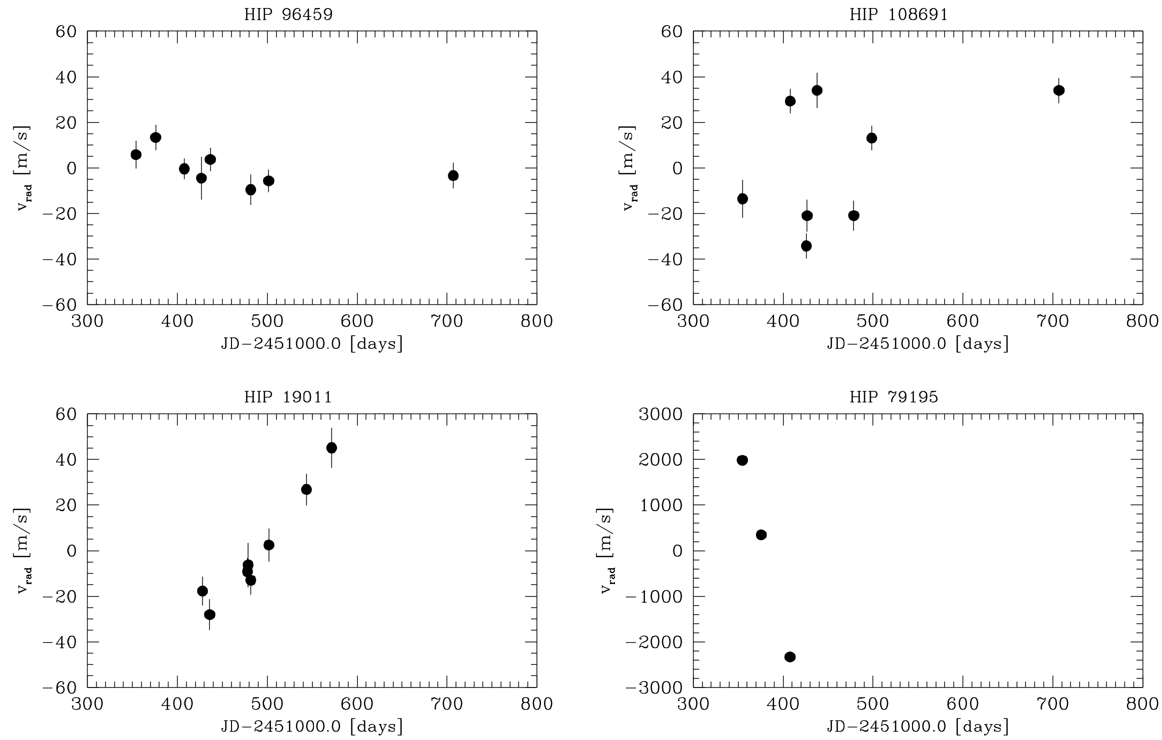

Fig. 4.— Observed radial velocities (with arbitrary zero points) versus time for four stars of the CAT proxy sample. HIP 96459 is one of the stars with the smallest radial velocity scatter in our sample; the observations are consistent with a constant radial velocity within the errors. HIP 108691 is a more typical star; the intrinsic velocity scatter is $23\,\mathrm{m\,s^{-1}}$, and the velocity pattern looks random. In contrast to this, the radial velocities follow a trend for HIP 19011, although its overall intrinsic velocity dispersion is even a little lower than the one for HIP 108691. Finally, HIP 79195 is an example for a spectroscopic binary which is easily identified. Note the different scale in the last panel, which makes the error bars smaller than the plotting symbols.

Similarly, short- and long-term periods have been derived for the K giant β Oph (Hatzes & Cochran 1996), and long-term periods of the order of 1.5–2 years for β Gem, π Her (Hatzes & Cochran 1999) and α Tau (with additional night-to-night variations of $100\,\mathrm{m\,s^{-1}}$, Hatzes & Cochran 1993). Moreover, Walker et al. (1989) observed a sample of five K giants and one K supergiant (including Arcturus, β Gem and α Tau), and *all* of the stars in this small sample showed long-term radial velocity variations over the course of one year with amplitudes between 30 and $300\,\mathrm{m\,s^{-1}}$, suggesting that these kind of variations are quite common.

The most likely explanation for these variations are radial pulsations for the short-term variations of a few days, and either non-radial pulsations or rotational modulation of surface features such as star spots for the long-term variations. There are a few indications for the mechanism that is responsible for the long-term variations. For example, Hatzes & Cochran (1994a) found evidence for a mode-switching in α Boo, which is only possible if the long-term variations are due to non-radial pulsations. However, α Boo and possibly β Oph (Hatzes & Cochran 1994b) seem to be the only K giants for which period changes have been observed so far. On the other hand, Walker et al. (1989) found a correlation of the long-term variations with chromospheric activity, Lambert (1987) observed variations in the He I line which were correlated with the radial velocity variations of α Boo, and Walker et al. (1992) found similar changes in the equivalent width of the Ca I line of γ Cep. These spectral line variations are likely

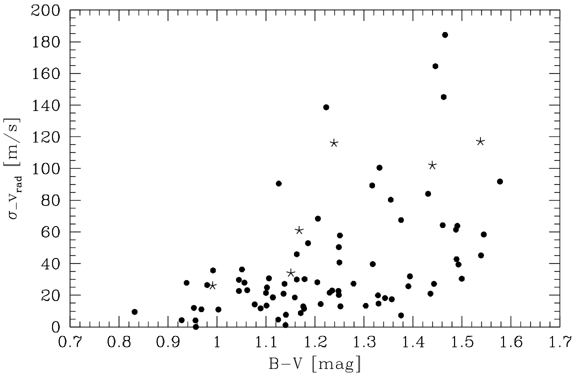

Fig. 5.— Dependence of the observed intrinsic radial velocity variability on $B-V$ color, taken from the Hipparcos Catalogue, for the stars in our proxy sample (filled circles). K giants from other investigations mentioned in the text are also shown (asterisks). There is a trend visible in the sense that redder K giants show larger radial velocity dispersions.

to be caused by the rotation of the star, and the related periods would correspond directly to the rotation period. Since the radial velocity variations show the same periodicity, this would clearly speak for rotational modulation of surface features as the mechanism producing these variations.

In principle there is a third possible explanation for the radial velocity variations: they could be caused by planetary companions. However, given the observed correlations with variability of spectral features, mode switching or photometric variability other explanations seem to be more likely, although planetary companions could still be present at least in a few cases. They could probably be detected with higher confidence if they were in rather elliptic orbits, imprinting the well-known characteristic shapes in the radial velocity curves. Another diagnostic tool which could help to detect the mechanism causing the radial velocity dispersions are spectral line bisector variations, which measure asymmetries in the spectral line profiles; they require rather high resolution and signal-to-noise data. Bisector variations are expected for both non-radial pulsations and rotational modulation, but not for planetary companions (Hatzes 1996).

Walker et al. (1989) noted that all six K giants in their sample were photometrically variable. This might be an important difference to the K giants in our proxy sample, which were selected not be detected as photometrically variable by *Hipparcos*.

Our results show that it is possible to find K giants with much smaller variations, at least on timescales up to one year and in a sample strongly biased against active, variable and multiple stars. The observed radial velocity dispersions are not expected to become much larger on longer timescales, since we already probed timescales of one year which is close to the observed periods for other K giants. For 18 stars we already have second year data, and for eight out of ten stars with intrinsic velocity dispersions smaller than $50\,\mathrm{m\,s^{-1}}$ these dispersions changed by less than $5\,\mathrm{m\,s^{-1}}$, typically only 1–$2\,\mathrm{m\,s^{-1}}$. For one more star (HIP 105497) the velocity dispersion changed by about $13\,\mathrm{m\,s^{-1}}$, but is still very small, and only one (HIP 80693) of the stars which would have been classified as good grid candidate before shows considerably more variations now.

Although we cannot identify the mechanism producing the observed dispersions with high confidence, it is unlikely that they are caused by planetary companions, which would affect their grid star properties, in contrast to the more likely explanations involving non-radial pulsations or rotational modulation of surface features. In any case, they are small enough to not severely affect the identification of binary stars among K giants, and we use the observed distribution of radial velocity dispersions as input parameter for Monte-Carlo simulations of radial velocity surveys designed to identify the binaries in a K giant sample.

4. A Strategy for the Whole Grid

After the selection of a candidate sample of K giants that might be suitable SIM grid stars it is essential for the astrometric stability of the grid to ensure the absence of stellar companions. While adaptive optics imaging and photometric monitoring could help to further vet the candidate sample from unwanted perturbers, a precise radial velocity survey of all grid stars is the most efficient way to identify a large fraction of the multiple stars in the candidate sample.

The following sections deal with the design of such a radial velocity survey. Any such survey will require a huge amount of observing resources from the ground, and it should be conducted as efficiently as possible. A separate photometric survey might be needed to provide an input sample for the radial velocity survey which is already cleaned from variable stars, in case it should turn out that photometric variability is correlated with intrinsic radial velocity variability and photometric variability information is not already available for the chosen kind of stars.

4.1. Simulation of a Radial Velocity Survey

We carried out simulations of a radial velocity survey of 3000 stars with an assumed binary frequency of 50% and determined the number of binaries that would escape detection for various observing scenarios. We also counted the number of single stars that would erroneously be rejected as grid stars, as well as the number of missed binaries that would produce an astrometric jitter larger than $1\,\mu$as in the *SIM* solution. For both single and double stars we added intrinsic radial velocity variations with a gaussian distribution (mean $20\,\mathrm{m\,s^{-1}}$, dispersion $12\,\mathrm{m\,s^{-1}}$), in accordance with the results of our proxy sample observations.

The orbit parameters for the binary stars were chosen to follow the observed distributions for other samples. The logarithm of the period P was generated according to a gaussian distribution with a mean of $\overline{\log P[\mathrm{days}]} = 4.8$ and a dispersion of $\sigma_{\log P[\mathrm{days}]} = 2.3$ (Duquennoy & Mayor 1991). The eccentricities e were distributed according to $f(e)\,\mathrm{d}e = 2e\,\mathrm{d}e$, as indicated in the same sample from Duquennoy & Mayor (1991). However, for systems with periods less than 100 days the eccentricities were set to zero, since Boffin et al. (1993) found a circulization period of about 100 days in a sample of 213 spectroscopic binaries with late-type giant primaries. Boffin et al. also analyzed the distribution of secondary masses in their sample and found no significant deviation from a uniform distribution. Hence, we assumed a fixed mass of $1\,\mathrm{M}_\odot$ for the K giant primary in our simulated sample and distributed the secondary masses uniformly in the mass range between $0.08\,\mathrm{M}_\odot$ and $1.0\,\mathrm{M}_\odot$. Random orientation of the orbits in space leads to a uniform distribution of periastron lengths ω and a distribution of the inclination angle i according to $f(i)\,\mathrm{d}i = \sin i\,\mathrm{d}i$. Face-on orbits with small inclinations are thus much less common than edge-on orbits, which is favorable for the detection of radial velocity signals.

The parameters that we varied include the radial velocity precision (from $0\,\mathrm{m\,s^{-1}}$ to $200\,\mathrm{m\,s^{-1}}$), the number of observations for each star (between 2 and 10), and the duration of the survey (up to 8 years). Furthermore, we adjusted the threshold of the reduced χ^2 (for a constant model radial velocity) above which a system is flagged as suspected binary; this corresponds to constraining the tolerated number of rejected true single stars and also roughly to the total number of systems that have to be observed.

For the models with two observations per star, the spacing between them corresponds to the survey duration. For the other models the additional observations were distributed randomly over the survey duration.

For the calculation of the astrometric jitter in the *SIM* solution it was assumed that each grid star will be observed twice during each of altogether 23 grid campaigns, spaced ten days apart. The interval between two subsequent grid campaigns was set to 40 days. A linear least squares fit to the observed positions was performed, which allowed part of the orbital motion to be absorbed as proper motion. The remaining scatter in the positions, corresponding roughly to half the value of the largest deviation of the star from a line connecting its position at the beginning and at the end of the mission, was used as a measure for the astrometric jitter.

For each parameter set we performed 10 000 simulations and obtained the mean percentages of truly single stars, unidentified binaries and unidentified binaries that would produce an astrometric jitter larger than $1\,\mu$as in the final composition of the grid. We also determined dispersions around these mean values for various realizations of samples with the same input parameters.

The parameter values for our reference model are as follows:

- duration of the survey: 5 years
- measurement accuracy: $20\,\mathrm{m\,s^{-1}}$
- number of observations per star: 2
- tolerated fraction of rejected single stars: 32.5%

This results in a binary fraction of 32.2±0.9%

in the final grid sample, with 3.6±0.5% of all grid stars displaying astrometric jitter in excess of 1 μas. It would require to observe two times as many stars as ultimately needed for the grid.

4.2. Discussion of the Simulation Results

The results of our simulations are presented in Figs. 6, 7 and 8. Fig. 6 illustrates the fractions of stars that will be erroneously rejected as single stars or missed as binary stars, respectively, as a function of the threshold in the computed χ^2. The top panel shows the results normalized to the total number of single and binary stars in the input sample. If one is willing to tolerate a success rate in identifying true single stars of only 50%, this results in a lower fraction of missed binaries of 23.4% as compared to 32.1% in our reference model, which only allows a fraction of 32.5% of the true single stars to be rejected as grid stars.

However, such a high rejection rate of single stars would vastly increase the number of stars in the input sample for the radial velocity survey (see middle panel of Fig. 6). In our reference model, we required that no more than twice as many stars have to be observed than finally needed for the grid, resulting in a tolerated rejection rate of single stars of 32.5% (and a χ^2 of 0.524 in the reference model, indicated by the dotted lines in Fig. 6). For a tolerated rejection rate of 50%, the radial velocities of about three times as many stars as finally needed for the grid would have to be analyzed. Besides the problems of finding so many suitable grid candidate stars, this dramatically increases the required observing resources, while only marginally improving the results: though the success rate in identifying binaries improved by about 10%, the fraction of unidentified binaries present in the grid will still be 31.9%, as compared to 32.2% in the reference model, and the number of unidentified binaries with astrometric signatures larger than 1 μas decreases only from 3.6% to 3.4%. The reason for these very small improvements is the increase in the number of stars in the input sample, which requires a larger success rate for the identification of binaries in order to achieve the same binary contamination fraction in the final grid. These effects almost cancel out, leading to only very small improvements for the final grid.

However, the bottom panel of Fig. 6 (which is a closeup of the lowest part of the middle panel)

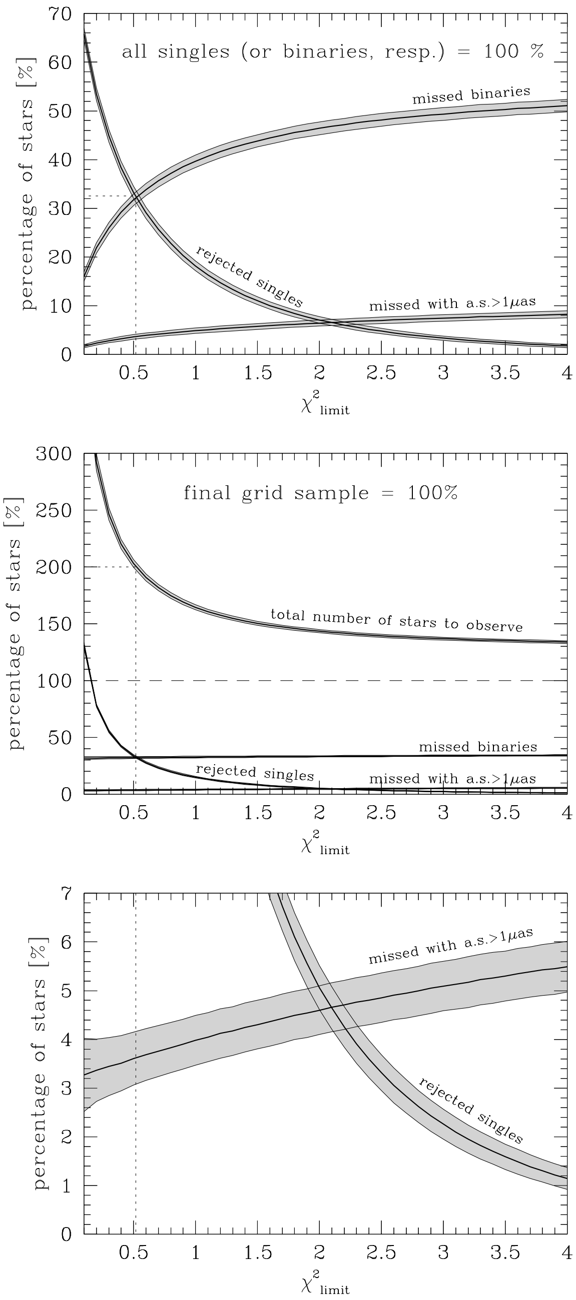

Fig. 6.— Fractions of single and binary stars that would be missed in a radial velocity survey as a function of the threshold in the computed χ^2. Values in the upper panel are normalized to the respective number of single and binary stars in the input sample, whereas in the other two panels they are normalized to the final composition of the grid. The dotted lines indicate the value of $\chi^2_{\rm limit}$ that corresponds to observing twice as many stars as needed for the grid.

shows that there is still some merit in observing a larger number of stars. Lowering the tolerated rejection rate of single stars to only 2% would result in a 5.4% contamination of the grid with binaries that would produce an astrometric jitter larger than 1 μas, as compared to 3.6% for the reference model. The gain in the number of stars that would have to be observed is not so large as to justify this degradation (especially since every effort should be made from the ground to define a grid as clean as possible, see below): still 1.3 times as many stars as needed for the grid would have to be observed. Observing two times as many stars as finally needed for the grid is also a reasonable number considering the fact that, given an assumed overall binary frequency of 50%, there will be just as many true single stars in the input sample as needed for the grid, and therefore we adopted the corresponding value of 32.5% for the tolerated rejection rate as our reference value.

4.3. Fine-tuning the parameters

Figure 7 shows the influence of some basic parameters of the radial velocity survey (accuracy of the radial velocities, the number of observations and the duration of the survey) on the final composition of the grid. As expected, the accuracy of the radial velocities has a mild influence on the ability to reliably identify binary stars. In the theoretical case of infinitely accurate radial velocities one still would end up with a 2.7% contamination in the grid by binary stars with astrometric jitter larger than 1 μas, while an accuracy of 200 $\mathrm{m\,s^{-1}}$ would lead to a contamination level with these stars of 9.6%. The reason why there are still a number of unwanted binaries left in the grid even in the case of infinitely accurate radial velocities is the intrinsic radial velocity scatter for K giants of about 20 $\mathrm{m\,s^{-1}}$, as discussed in Sect. 3. It does not seem very meaningful to measure radial velocities which are significantly more precise than the expected intrinsic scatter, and our reference value of 20 $\mathrm{m\,s^{-1}}$ for the precision of the radial velocity measurements reflects this situation. On the other hand, 20 $\mathrm{m\,s^{-1}}$ is exactly the accuracy which one could achieve with Keck for a 12 mag K giant in a 2 minute exposure, already comparable to the readout time. At a 3m class telescope, one could probably achieve 50 $\mathrm{m\,s^{-1}}$ in a 3 minute expsosure, but this would already result in a higher

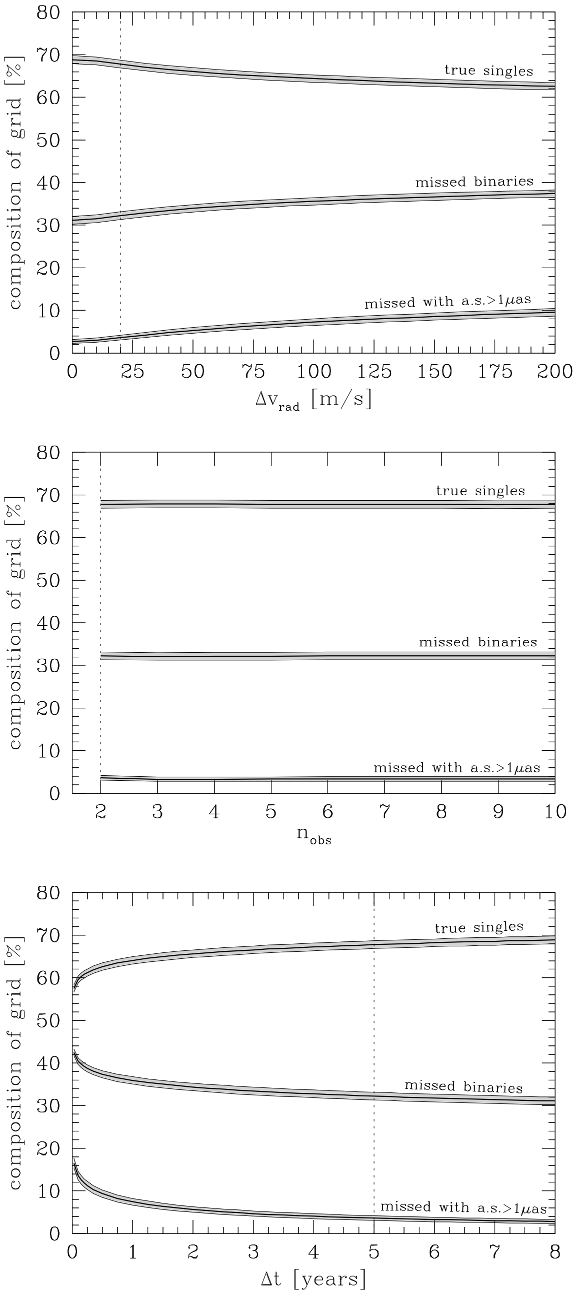

Fig. 7.— Influence of radial velocity accuracy (upper panel), number of observations (middle panel) and survey duration (lower panel) on the final composition of the grid according to our simulations. The dotted lines indicate the values of our reference model; see text for details.

contamination fraction in the final grid of 5.3%. So $20\,\mathrm{m\,s^{-1}}$ seems to be a good compromise, resulting in a 3.6% contamination of the grid with binary stars producing an astrometric jitter larger than $1\,\mu$as.

The most surprising parameter in our reference model might be the low number of only two observations per star. Indeed, at least if the survey is conducted with sufficient precision, virtually every binary star up to a certain period can be identified already by the change in radial velocity over a five year interval (see also Fig. 8). Additional observations in between these two observations only help to identify the very few binaries with periods which are integer fractions of the interval between observations, so that in the scenario with three observations per star the contamination rate of the grid with binaries with astrometric signatures larger than $1\,\mu$as is 3.3% as compared to 3.6% in the reference model. Adding even more observation does not decrease the contamination fraction any further; it basically remains constant for three observations onward for the models with a radial velocity accuracy of $20\,\mathrm{m\,s^{-1}}$. For a degraded radial velocity accuracy, it takes more observations per star to achieve the lowest possible contamination level, though it will always be higher than the one for surveys with better precisions. In other words, it is not possible to make up for lower precision radial velocities with scheduling more observations per star. For example, with a radial velocity precision of $50\,\mathrm{m\,s^{-1}}$ the asymptotic contamination level of 4.7% is reached with four observations per star, while with a radial velocity precision of $200\,\mathrm{m\,s^{-1}}$ a level of 7.9% is only reached after eight observations per star.

Finally, the longer the interval between the first and the last observation, the higher the sensitivity towards the identification of longer period binaries will be. An increase in the survey duration from five years as in our reference model to eight years will decrease the contamination level of the final grid with binaries producing astrometric jitter larger than $1\,\mu$as from 3.6% to 2.8%. A 20 year baseline for the radial velocities even would decrease the fraction down to 1.9%. This is quite remarkable, all the more since it is achievable without any additional amount of observing resources. However, the value of five years which we chose for our reference model reflects the maximum time that we realistically could assume to have left before the launch of *SIM*. On the other hand, scheduling the second observations only two years after the first observations would result in a 5.6% contamination fraction with binaries producing astrometric jitter in excess of $1\,\mu$as. Our simulation results underline the importance of a timespan as large as possible in between individual radial velocity observations in order to achieve the lowest possible contamination fraction of the grid with unwanted stars.

4.4. Properties of missed binary stars

It is very important to know not only how many binaries will be missed in a radial velocity survey and contaminate the grid, but also the characteristics of these multiple systems. We plotted the distributions of periods, semi-major axis, inclinations and astrometric jitter as seen by *SIM* in our generated input sample as well as in the sample of binary stars that escape detection in the radial velocity survey (Fig. 8). Those binaries left in the grid that will produce the largest astrometric jitter are also marked.

The first thing to note is that basically all binaries with periods less than 10 000 days can be identified, except for a few systems with periods which are integer fractions of the interval between observations (Fig. 8, upper left). For systems with periods greater than 1 million days (2700 years) the success rate in identifying the stars as binaries decreases drastically. Fortunately these are the systems that will not impose a major problem for the *SIM* grid; their astrometric jitter will be small, since the periods are so large compared to the *SIM* mission duration that no orbital curvature will be detected.

The systems that would produce a measurable astrometric jitter if included in the grid are those with periods around 100 000 days. Corresponding semi-major axis are mostly less than 100 AU, typically even less than 50 AU (Fig. 8, upper right). Any additional observing program aimed at further reducing the fraction of binary stars in the final grid should be designed to be sensitive to these kind of systems. In the optical, the magnitude difference between a K giant and an M dwarf could be as high as 8–12 mag, which would make direct detections rather difficult. Infrared adaptive optics imaging might offer a favorable advantage.

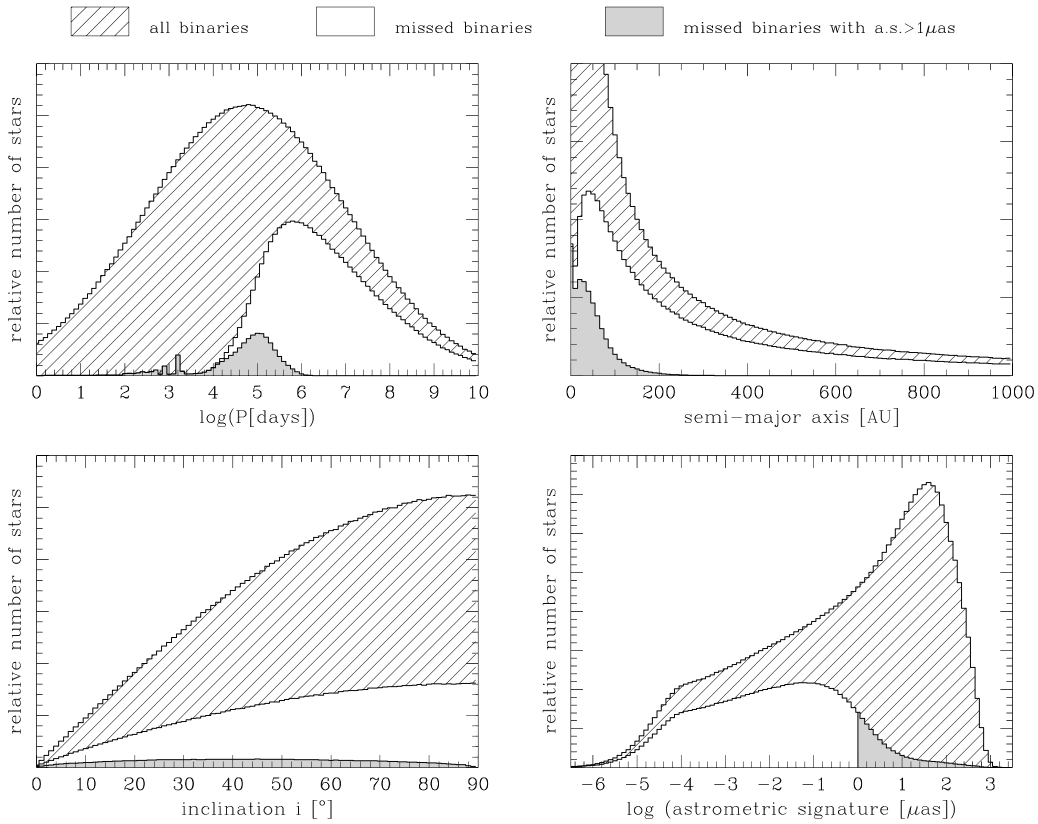

Fig. 8.— Distribution of periods, semi-major axis, inclinations and astrometric signatures as seen by *SIM* in our simulated binary input sample (hatched), among the sample of binaries that would be missed in our reference radial velocity survey (white), and among the subset of the latter with astrometric signatures larger than 1 μas (grey). The peaks in the period distribution with periods of 5 years and less stem from observing the star during the same phase of the orbit; they could be eliminated from the final grid by scheduling one more observation for all stars. The lower right plot nicely demonstrates the power of a radial velocity survey in identifying the vast majority of stars that would cause major problems for the *SIM* grid.

The Tycho-3 project which is now starting in Copenhagen could also be of use for the selection of *SIM* grid stars. While the variability data in Tycho-2 are rather incomplete especially at the faint end relevant for the *SIM* grid, this situation should vastly improve in Tycho-3. Tycho-3 will also supply duplicity data which could help to eliminate wide binaries from the grid; however, the large number of shorter period binaries, causing greater astrometric signatures when included in the grid, will still escape detection in the Tycho-3 reductions due to the large distance of the grid stars.

For a number of systems with projected separations in the range $\approx 0.01-1''$ and small magnitude differences *SIM* would detect double star fringes. However, this is not a big concern since those stars could be eliminated from the grid after only one or two *SIM* observations.

The distribution of astrometric jitter as seen by *SIM* in the binary input sample as compared to the sample of unidentified binaries (Fig. 8, lower right) illustrates nicely the power of a radial velocity survey in identifying preferrably those stars which would cause the largest astrometric jitter. Without such a survey, the *SIM* grid would encounter serious problems.

5. Discussion

Cleaning up a pre-selected sample of candidate grid stars from binaries with a radial velocity survey requires a huge amount of observing resources; estimates are 100 nights at a 10 m telescope or 500 nights at a 3 m telescope for 1500 suitable grid stars. If we knew for sure that the resulting contamination fraction in the grid would not be larger than that derived in our Monte-Carlo simulations in the last section, it probably would not be justified to perform the radial velocity survey with such a high accuracy as assumed in our reference model.

However, there are quite a number of uncertainties involved that could increase the number of unusable grid stars.

First, we do not know whether the true binary frequency and the distribution of orbital parameters in a grid candidate input sample match those that we used for our Monte Carlo simulation. They were derived for a sample of main sequence field stars and could be quite different for K giants in general and for Halo K giants in particular, although there are no indications for this so far (Abt 1983; Harris & McClure 1983; Boffin et al. 1993; Latham 2001). Shifting the maximum in the period distribution to only slightly larger values however could have meaurable effects for the stability of the grid (cf. Fig. 8, upper left).

Second, we are not able to identify planetary companions to such a large number of stars. Jupiter-mass companions orbiting within 1 AU will not cause a measurable astrometric jitter for *SIM* if the grid objects are located at large enough distances, i.e. larger than about 2 kpc. However, if giant Jupiters in orbits of the order of 5 AU are common this will add to the overall number of unusable grid stars.

Third, stars can be unsuitable as grid stars for other reasons than duplicity. Phenomena that could produce photocenter shifts include starspots, planetary transits and astrometric microlensing. The angular diameter of a K giant at 2 kpc is of the order of 50 μas. Thus, in order to produce a measurable astrometric jitter for *SIM*, the photocenter shift would have to be of the order of 10–20 % of the stellar radius. Most starspots are probably not large and cool enough to produce such a giant shift, but there might be a few rare cases where this appears to be possible. Strassmeier (1999) determined the size of the largest starspot known to date on an active and variable K giant; it covers about 11 % of the entire stellar surface. While such spots are probably not very common, the chances for facing this problem in the *SIM* grid could be minimized by a pre-selection of candidate grid stars in the input sample against variable and active stars.

Planetary transits are not a big concern either. The radius of a giant planet is about hundred times smaller than that of a K giant, and even if the planet completely occulted part of the stellar surface the induced positional offset in the measured photocenter would be too small to be recognized by *SIM*.

The case might be different for astrometric microlensing. While photometric microlensing is only detectable when the source and the lens are perfectly aligned, the optical depth is much larger for astrometric microlensing which aims at detecting directly the deflection of starlight as it passes close to another body. Miralda-Escudé (1996) estimated that several events could be detected with an astrometric precision of 10 μas by monitoring many thousand stars over several years.

Finally, there might be additional phenomena causing astrometric jitter that we have not thought of or do not know of yet. Since all these could add to the contamination fraction in the *SIM* grid, it is crucial for the stability of the grid to identify as many problematic stars as possible before the mission, from the ground. Any stars that are left in the grid that are not as astrometrically stable as required could affect the observations where these stars have been used as grid stars. Besides affecting individual observations, a larger number of grid star observations have to be scheduled along with each science observation for a higher contamination fraction in the grid, taking precious *SIM* observing time. Using *SIM* itself for culling unsuitable grid stars is clearly much more expensive than doing a thorough job from the ground.

6. Summary

We have argued for K giants as the best type of stars for use with the *SIM* grid. Due to their high intrinsic luminosities K giants can be located at much larger distances than any other type of star. K giants around 12 mag would be located at about 2 kpc for solar metallicity and up to 5 kpc if they were metal-weak, thus reducing any kind of astrometric jitter that could stem from stellar and planetary companions as well as from other unknown sources.

We have shown that radial velocities can be measured precisely enough to identify problematic companions to K giants. The intrinsic radial velocity scatter is of the order of $20\,\mathrm{m\,s^{-1}}$ for most of the stars in a proxy sample of *Hipparcos* K giants which is highly biased against multiple and variable stars. A few spectroscopic binaries that were included in our sample due to lack of information in the Hipparcos Catalogue were easily identifiable as such with only two or three observations. We are in the process of extending our precise radial velocity measurements to a statistically unbiased sample of K giants.

We simulated the possible design of a radial velocity survey of several thousand stars. We find that the measurement precision and the timespan over which the radial velocities are measured are of great importance, whereas the number of observations has only marginal effects on the result. Our preferred scenario — two radial velocities measured five years apart with a precision of $20\,\mathrm{m\,s^{-1}}$ for every star — would result in a 32% contamination of the final grid with binary stars, but only 3.6% of the stars in the grid would produce astrometric jitter larger than $1\,\mu$as.

Any such radial velocity survey would require large amounts of observing resources. However, since the astrometric stability of the grid is a crucial element for the success of the Space Interferometry Mission in its entirety, any ground-based efforts ensuring the required astrometric quality of the grid seem to be justified.

Our sincere thanks go to Geoff Marcy and Paul Butler, who kindly let us use their setup and reduction software, without which the precise radial velocity measurements of this study would not have been possible. We would like to thank the referee, Sean Urban, for his comments which helped to improve the manuscript. S.F. and A.Q. gratefully acknowledge support from NASA's SIM Preparatory Science Program.

A. Selection Criteria

The criteria which we used to select the Hipparcos proxy sample and the Tycho-2 sample are described in Tables 3 and 4, respectively. They were designed to ensure that every possible star with low astrometric quality or indications for duplicity or variability was rejected. They are rather strict, and it is likely that a number of suitable stars also got rejected. A number of the criteria are very similar, and many stars are rejected by more than one criterion. Most of the criteria listed refer to flags or parameters as given directly in the Hipparcos, TRC, Tycho-1 and Tycho-2 catalogs, respectively. However, in order to sort out possible astrometric binaries among our sample we performed a comparison of the proper motions in the Hipparcos and ACT/TRC catalogs, testing whether the 'instantaneous' Hipparcos proper motion (derived from measurements collected over a timespan of 3 years) is consistent with the proper motion determinations based on a larger epoch difference (≈ 80 years for ACT/TRC). Significant differences might reflect orbital motions due to companions. We followed the approach by Wielen et al. (1999) who defined a test parameter F which is basically the ratio of the proper motion difference and its expected error in both directions of the error ellipsoid. A star is classified as 'single-star candidate' when $F < 2.49$, corresponding to a 2σ criterion. This lead to the criteria 14–17 listed in Table 3.

Table 3

Selection criteria applied to Hipparcos stars

		astrometry	
1	H29	[percentage of rejected data]	0%
2	H30	[goodness-of-fit statistic]	< 3
3	q_pm	[TRC quality flag for proper motion]	≤ 2
		variability	
4	H6	[coarse variability flag]	$\sqcup$
5	H46	[scatter of Hp observations]	$< 0.1\,\mathrm{mag}$
6	H52	[type of variability]	$\sqcup$
7	T47	[previously known or suspected as variable]	$\sqcup$
8	T48	[variability of the Tycho measurements]	$\sqcup$
		duplicity	
9	H2	[proximity flag]	$\sqcup$
10	H55	[CCDM identifier]	$\sqcup$
11	H59	[double and multiple systems annex flag]	$\sqcup$
12	H61	[suspected non-single]	$\sqcup$
13	ACTflg	[proper motion difference TRC-ACT]	$\sqcup$
14	$\Delta\mu_{\mathrm{TRC,HIP}}$	[total proper motion difference TRC-HIP]	$< 10\,\mathrm{mas/a}$
15	$F_{\mathrm{TRC,HIP}}$	[significance of $\Delta\mu_{\mathrm{TRC,HIP}}$]	< 2.49
16	$\Delta\mu_{\mathrm{ACT,HIP}}$	[total proper motion difference ACT-HIP]	$< 10\,\mathrm{mas/a}$
17	$F_{\mathrm{ACT,HIP}}$	[significance of $\Delta\mu_{\mathrm{ACT,HIP}}$]	< 2.49

Table 4

Selection criteria applied to Tycho-2 stars.

		astrometry	
1	g_mRA	[goodness of fit for mean RA]	≤ 2
2	g_mDE	[goodness of fit for mean Dec]	≤ 2
3	g_pmRA	[goodness of fit for pmRA]	≤ 2
4	g_pmDE	[goodness of fit for pmDE]	≤ 2
		photometry	
5	$\sqrt{e\_B_T{}^2 + e\_V_T{}^2}$	[combined standard error in B_T–V_T]	$\leq 0.3\,\mathrm{mag}$
		duplicity	
6	pflag	[mean position flag]	$\sqcup$
7	prox	[proximity indicator]	999
8	posflg	[type of Tycho-2 solution]	$\sqcup$

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