Preparing the PRIMA Astrometric Planet Search: Selecting Suitable Target and Reference Stars

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ABSTRACT

ESO's PRIMA (Phase-Referenced Imaging and Micro-arcsecond Astrometry) facility at the VLT Interferometer on Cerro Paranal in Chile is expected to be fully operational in only a few years from now. With PRIMA/VLTI, it will then be possible to perform relative astrometry with an accuracy of the order of 10 microarcseconds over angles of about 10 arcseconds. The main science driver for this astrometric capability is a systematic search for extrasolar planets around nearby stars.

Target stars as well as reference stars for this astrometric planet search have to be very carefully chosen in order to make the measurements robust and effective. Most importantly, reference stars have to be astrometrically stable to only a few microarcseconds in order to provide a suitable reference for the astrometric measurements. Target stars should be located at small distances so that a possible planet would cause a detectable astrometric signal. Moreover, a suitable target star and a suitable reference star have to be found within about 10 arcseconds of each other to ensure the highest accuracy and effectiveness, which obviously requires some trade-off in the final target list. Possible strategies and preparatory observations for the assembly of a suitable target list for the astrometric planet search with PRIMA/VLTI will be discussed.

Keywords: PRIMA, VLTI, Interferometry, Extrasolar Planets, Astrometry, Reference Star

1. INTRODUCTION

ESO's PRIMA (Phase-Referenced Imaging and Micro-arcsecond Astrometry) instrument at the VLTI on Cerro Paranal in Chile is expected to be fully operational by 2006, enabling differential astrometric measurements with an accuracy of about 10μas (see the overview paper by Quirrenbach et al.[1] in this volume). The primary science driver for microarcsecond astrometry is a survey for extrasolar planets around nearby stars using the 1.8 m Auxiliary Telescopes (AT's). A prerequisite for precise differential astrometry at this level is the careful selection of suitable targets as well as reference stars, so that potentially problematic stars with unmodeled motions and/or photocenter shifts can be avoided.

This is particularly challenging when taking into account that the best astrometric measurements that are available today for the vast majority of the target stars are from Hipparcos and have a precision of about 1 mas, two orders of magnitude larger than the PRIMA goal. Even worse, for many of the potential reference stars no astrometric measurements will be available at all, due to their faintness. Thus potential astrometric stability of target as well as reference stars has to be inferred indirectly from other measurements as well as from modeling.

The Space Interferometry Mission (SIM) is facing the same challenges in terms of astrometric reference stars. However, in contrast to PRIMA, where an astrometrically unstable reference star renders only the corresponding target star measurements unusable, a bad reference star in SIM's astrometric grid will influence all other astrometric measurements in wide-angle mode since they are all linked together by the astrometric grid. The scenario in SIM's narrow-angle mode, where additional astrometric reference stars close to the target are needed to achieve higher astrometric precision than in wide-angle mode, is comparable to PRIMA.

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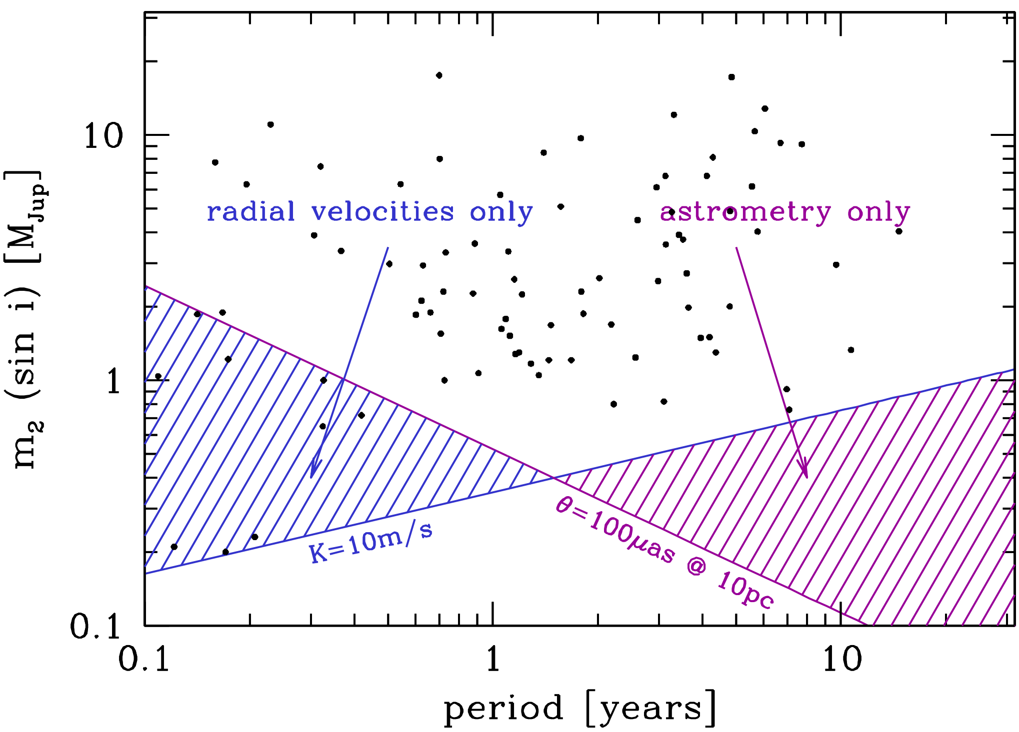

Figure 1. Comparison of the discovery space for extrasolar planets with the radial velocity and the astrometric technique. The smallest detectable planet mass (times the $\sin i$ uncertainty for the case of the radial velocities) is plotted against the period of the planet in logarithmic units (solid curves), for a semi-amplitude K of the radial velocity signature of 10 m/s, and for an astrometric signature (peak-to-peak) of 100 μas at a distance of 10 pc. Known planetary systems detected with the Doppler technique are indicated as small dots. From this plot it is evident that for the given accuracies of each technique, the astrometric technique becomes more sensitive at periods longer than about 1–2 years.

This explains why special care has been taken in developing a strategy to select the SIM grid stars[2, 3, 4]. A precise radial velocity survey of the order of several thousand stars is needed, designed to reject a large percentage of potentially unsuitable short- and intermediate-period binary stars among the grid candidates. Binary stars with periods longer than a few thousand years, located at distances of 1–2 kpc, will not cause astrometric jitter larger than 1 μas and are thus suitable reference stars. For binary stars with intermediate periods (several tens to several thousands of years), additional acceleration terms have to be introduced in the astrometric solution to account for orbital motion.

A precise radial velocity survey to ensure the quality of the astrometric reference stars is not feasible for PRIMA, both in terms of observing load as well as project timescale. However, on average the PRIMA reference stars will be much fainter than the SIM grid stars. Thus the PRIMA reference stars are located at larger distances, and any residual astrometric jitter will appear smaller. In the following, we present a first approach towards finding suitable PRIMA targets and reference stars.

2. COMPARISON OF THE RADIAL VELOCITY AND THE ASTROMETRIC TECHNIQUES

The primary goal of 10 microarcsecond astrometry is a survey for extrasolar planets around a sample of the order of 100 stars. Whereas the radial velocity technique, with which virtually all extrasolar planets known today have been found, is most sensitive to close-in planets with short periods, the astrometric technique is most sensitive to planets in wide orbits with longer periods; a limit on the detectable periods is only set by the survey duration. This is due to the fact that the Doppler technique measures velocity changes, which are highest for short periods, whereas the astrometric method looks at shifts in the positions of the target stars, which are largest for wide orbits. The astrometric signature θ, i.e. the peak-to-peak angular displacement of the star over the full orbit, is given for the case of a circular orbit by Kepler's Third Law:

$$\theta_{\text{circ}} = 191\,\mu\text{as} \cdot \frac{P\,[\text{yr}]^{2/3} \cdot m_2\,[\text{M}_J]}{d\,[10\,\text{pc}] \cdot m_1\,[M_\odot]^{2/3}},$$

where P is the period in years, m_2 the companion mass in Jupiter masses, d the distance in parsec, and m_1 the mass of the primary in solar masses. For eccentric orbits with eccentricity e, the astrometric signature θ becomes:

$$\theta = \theta_{\text{circ}} \cdot \sqrt{1 - (e \cdot \sin\omega)^2},$$

where ω denotes the longitude of the periastron.

The discovery space for radial velocities and astrometry is compared in Fig. 1. Assuming that the most precise radial velocity surveys can detect a planet with a semi-amplitude of 10 m/s, and that the most precise astrometric surveys (for the moment) can detect systems with a peak-to-peak astrometric signature of $100\,\mu$as, then assuming a distance of 10 pc for the target star, the astrometric method becomes more sensitive (i.e. can detect smaller mass planets than the Doppler technique) for periods longer than about 1–2 years. Of course the astrometric signature of a certain planet depends on the distance, whereas the radial velocity signature is independent on the distance, so that for stars closer than 10 pc the astrometric technique is superior to the radial velocity technique even for smaller periods than 1 year, whereas for stars that are further away than 10 pc the radial velocity technique might still be more sensitive to smaller mass planets than the astrometry for periods of several years.

3. TARGET STARS

The target stars for the Astrometric Planet Search with PRIMA will be selected to address a variety of scientific questions that cannot be tackled with the radial velocity (RV) observations:

- **What are the masses of the detected radial velocity planets? Are the orbits of the various planets in planetary systems coplanar?**

  The corresponding target stars to address these questions will clearly be those that harbor planets that have already been detected with the radial velocity technique. Right now, there are not very many of these systems that are suitable for astrometric observations with PRIMA, mainly due to the lack of nearby reference stars or because they are not observable from Paranal. Furthermore, approximately 25% of the radial velocity planets detected by today have minimum astrometric signatures calculated to be smaller than $20\,\mu$as, too small to be detectable with PRIMA. However, if the inclination for these orbits is small, the astrometric signature will be larger and might be detectable, even if the chances for small inclinations are low. In any case, those radial velocity planets that have suitable astrometric reference stars nearby will certainly end up in our final target list.

- **How do the properties of planets orbiting early-type stars differ from those around later-type stars, and of planets orbiting young stars from those orbiting older stars?**

  In order to address these questions, target stars that are not suitable for precise radial velocity observations like early-type stars and young stars have to be observed with PRIMA. Our plan is to observe a number of A and F stars as well as some of the youngest stars in the solar neighborhood. The inversely linear scaling of the astrometric signature with distance however prohibits the use of stars that are further away than about 100–150 pc, and at distances larger than about 100 pc the astrometric sensitivity to planets is already restricted to the most massive planets and the longest periods. In recent years, a number of smaller star-forming regions have been found at distances closer than 100 pc to the Sun (TW Hydrae association, Tucana/Horologium association, β Pic moving group). These probably present the best searching grounds

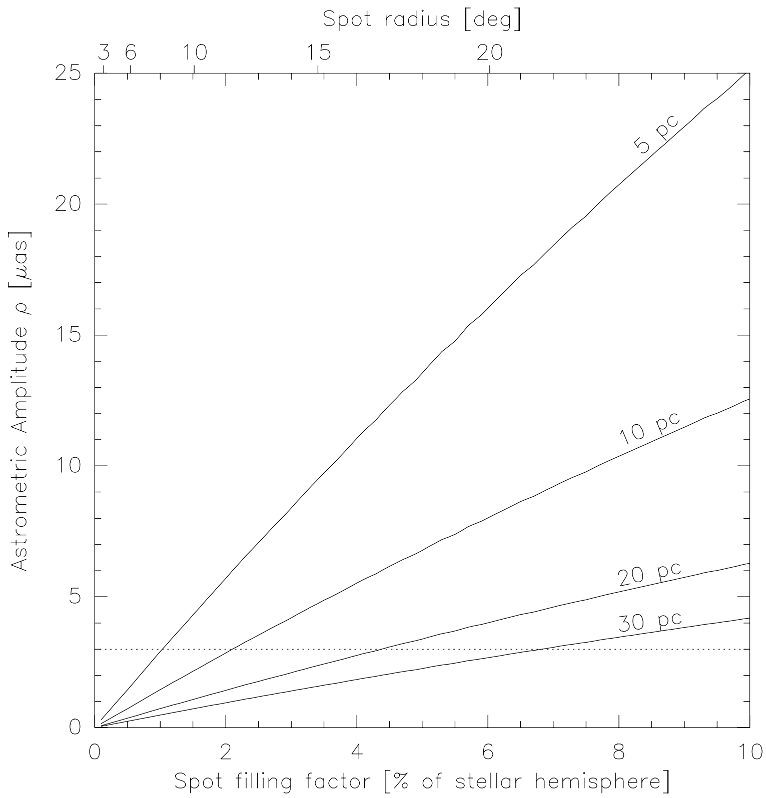

Figure 2. Angular displacement (one half peak-to-peak) of a solar-like star in the K band due to starspots as a function of filling factor and for various distances (solid lines). Assumptions are a limb darkening coefficient of 0.25, a radius for the star of $1\,R_\odot$, a photospheric temperature of 5800 K and a spot temperature of 4600 K, and an inclination of the rotation axis of 90° with the spot located at the equator. The dashed line indicates one third of the nominal PRIMA astrometric accuracy. For a star at a distance of 10 pc, a spot filling factor of 2% could already cause a photocenter shift affecting the astrometric accuracy.

for young targets for the astrometric planet search. However, since many of the larger nearby star-forming regions are located at a distance of 140 pc (e.g. Taurus-Auriga, ScoCen, Chamaeleon, Lupus), stars in these regions will probably also be included in our target list. Nearby young stars are identified and characterized e.g. in Ref. 7, 8, 9.

- **What is the lowest mass planet that we can find? What is the frequency of planets around M stars as compared to e.g. K stars?**

  The list of target stars for the PRIMA astrometric planet search will probably be complemented by those stars that present the best targets for an astrometric planet search: the closest and most lightweight stars that are out there. As a starting point for this category, we have selected the ten closest stars in each 0.1 $M_\odot$ mass bin between 0.08 and 1 $M_\odot$. Note that while for radial velocities there is a very large number of stars that can potentially be observed and screened for the presence of planets without much degradation in accuracy for the fainter and more distant stars (only limited by photon noise, which can be remedied by using larger telescopes), the target list for astrometric extrasolar planet surveys is much more limited and prioritized: the highest astrometric accuracy can be reached for the closest stars, spawning a renewed interest in the most nearby stars.

In order to make up a suitable target for an astrometric planet search, the target stars have to fulfill some more requirements. They should all be brighter than about 12 mag in K since they will be used for phasereferencing, but this is not a very limiting constraint for nearby stars. Of more importance is probably the fact that the photocenters of these targets should not shift by more than a few microarcseconds due to effects other than a potentially orbiting planet. This places a tight constraint on the size of potential starspots on these stars, especially for the young T Tauri stars which are often photometrically variable. We have simulated the astrometric displacement that a starspot would cause as a function of the filling factor and the distance of the star (Fig. 2). We assumed a photospheric temperature of 5800 K and a spot cooler by 1200 K. For maximum effect, the inclination of the rotation axis was assumed to be 90°, and the spot was placed on the equator. The limb darkening coefficient was taken to be 0.25 in the K band[5], appropriate for F and G stars, and the radius of the star was set to $1\,R_{\odot}$. The resulting astrometric displacement (one half peak-to-peak) in the K band is shown as a function of spot filling factor. E.g., for a solar-like star at 10 pc, a spot with filling factor larger than about 2% would already cause a photocenter shift of a few microarcseconds that would affect the astrometric accuracy, in agreement with the results by Hatzes[6]. Since due to spot lifetimes and spot distributions in case of various starspots this effect is very difficult to model, stars with spots that could potentially corrupt the astrometric measurements should best be avoided as target stars.

On the other hand, while spectroscopic binaries should be avoided as target stars due to the orbital motion that might be detectable in the primary as well as the potentially confusing light of the secondary, visual binaries might actually present an excellent class of objects for an astrometric planet search. A relatively bright reference star basically comes for free, and furthermore one gets to observe two targets at the same time since either component can be regarded a target. The drawback is that if a signal is detected, there is no easy way of telling around which component a planet might orbit, unless a third source in the field is observed as an additional outside reference to unambiguously establish the wobbling component.

4. REFERENCE STARS

A careful selection of reference stars is of great importance for the success of the astrometric planet search program. Reference stars should not display any amount of astrometric jitter larger than the measurement accuracy, and should thus be located at large distances to minimize any potential astrometric motions.

Since in the narrow-angle regime the astrometric error scales linearly with the separation between target and reference star[10], the reference star should be located close to the source. For typical atmospheric conditions on Paranal, von der Lühe, Quirrenbach & Koehler[11] estimate that the reference star should not be located more than $10''$ away from the target star, if the highest accuracy of about 10μas is required. Furthermore, reference stars should be brighter than about 16 mag in K.

As a starting point, we wanted to estimate the probability of finding a candidate reference star at a given angular separation and K magnitude. Based on star counts in a standard galaxy model, Shao & Colavita[10] estimated that in order for a 90% chance to find a reference star brighter than 16 mag in K, the field radius would have to be about $25''$ (averaged over all galactic latitudes). Creech-Eakman et al.[12] obtained photometry in the fields of almost 1000 nearby stars in order to characterize possible reference stars for astrometric searches for substellar companions with the Keck Interferometer, very similar to the needs of the PRIMA astrometric planet search. However, all these targets were in the northern hemisphere. Out of 733 usable fields, 203 fields (27.7%) had a possible reference star brighther than 17 mag in the Gunn i filter within $30''$. Scaling that very roughly to a probability of finding a (late-type) reference star brighter than K=16 mag within $10''$, we arrive at a probability of 12.3%. This is in excellent agreement with the scaled model results of 14.4% for a same size field by Shao & Colavita[10].

We used the 2MASS[13] as well as the USNO-B1.0[14] catalogs to search for potential reference stars around our targets. The 2MASS catalog has the advantage of very precise photometry in the K band, but it is complete only to a K magnitude of about 14.5 mag and thus is of limited use here. Nevertheless, it is instructive to look at these results. The USNO-B1.0 Catalogue on the other hand is very comprehensive and goes down to V=21 mag and thus may contain some stars which are actually too faint in K to be used as reference stars. As the target sample, we took for the moment all bona-fide main-sequence stars from the Catalog of Nearby Stars[15], in total 1734 sources. Around these, we searched for potential reference stars in the above mentioned catalogs with search radii of $10''$, $20''$ and $30''$. The result is plotted in Figure 3. The solid line designates the

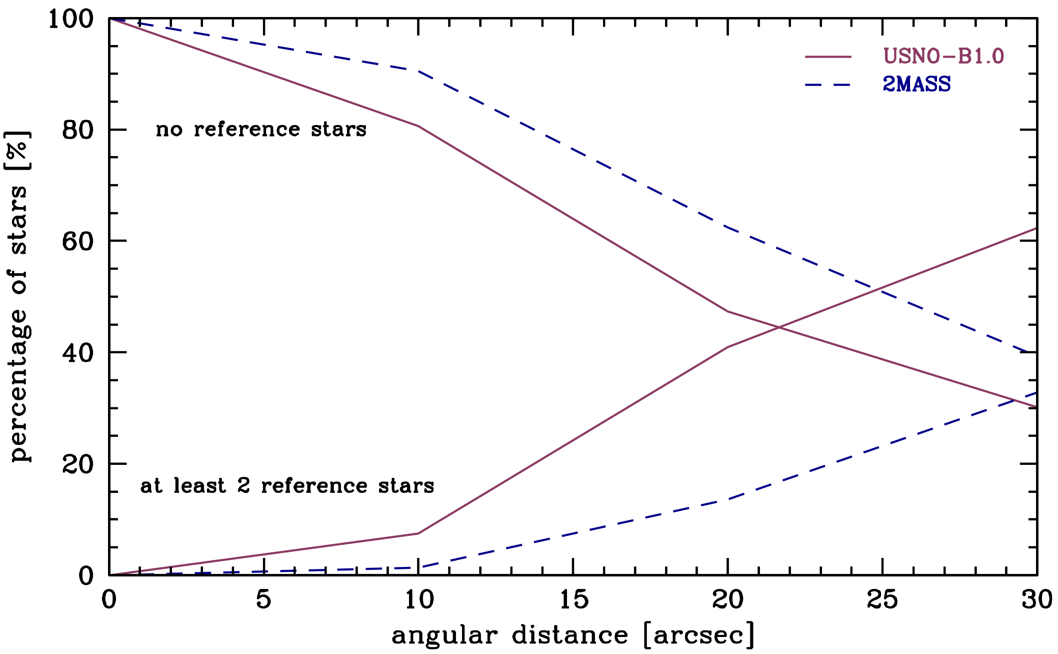

Figure 3. Percentages of possible reference stars in the USNO-B1.0 (solid lines) and 2MASS (dashed lines) catalogs. The input sample of possible target stars consisted of all main-sequence stars from the CNS3 catalog. The upper curves show the percentages of target stars with no reference stars at all, whereas the lower curves show the percentages of target stars that have two or more possible reference stars in that catalog.

results for the USNO-B1.0, the dashed line for 2MASS. The line starting at 100% labeled 'no reference stars' gives the percentage of stars within that search radius for which no potential reference at all could be found within that catalog. At a field radius of $10''$ that percentage is 81% for the USNO-B1.0 and 90% for 2MASS. As expected, the 2MASS catalog contains fewer than the expected 12.3–14.4% discussed above, whereas the USNO-B1.0 contains more, some of which will be too faint.

The two lower lines labeled 'at least 2 reference stars' denote the percentages of target stars in the input sample that have two or more potential reference star entries in the respective catalogs. For a field radius of $10''$, this percentage is 8% for the USNO-B1.0 and only 1% for 2MASS. Note that these percentages increase fast with larger field radius. This is partly due to the fact that in the crowded fields in the galactic plane many of the stars will have more than one reference star if the field size is large enough.

It could indeed be useful to have more than one suitable reference star available for the targets, since only then one can unambiguously establish whether a certain astrometric signal stems from the target or the source (similar to the case with a binary target discussed above). Furthermore, a large fraction of the potential reference stars will probably turn out not to be useful, because of their binary nature or anything else that might introduce astrometric jitter in the measurements. Assuming that this fraction of unsuitable reference stars might be 50% or even larger, one would want to start with target stars that have at least four or five potential reference stars in the field, of which two might turn out to be useful in the end. Fields in the galactic plane might be the best choices in this respect.

In addition to 2MASS and USNO-B1.0 we also tried to use the UCAC2 Catalog[16], which contains stars down to a magnitude of about 16 mag in a bandpass between V and R. However, it is stated that UCAC2 is not complete in that range; in particular, stars with separations of less than $3''$ are always missing, and even in the angular separation range from $3''$ to $6''$ most stars are missing. Since we were mostly interested in stars closer than $10''$ to another star, the current - preliminary - release of the UCAC catalog is not suited for that task. Subsequent editions that include the currently missing separation ranges might however be very useful for the

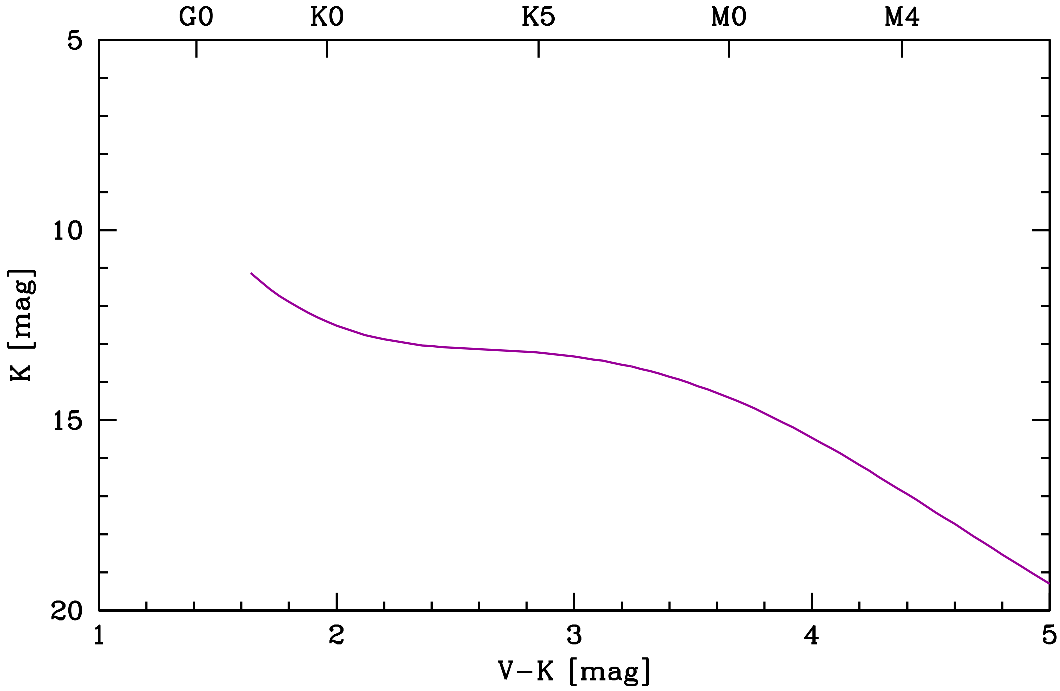

Figure 4. Minimum apparent magnitude in K as a function of $V - K$ color so that a potential Jupiter mass companion in a five year orbit would not be astrometrically detectable around a main-sequence star of the given color. For example, putative planets with the given properties around an M0 star ($V - K \approx 3.7$ mag) would not be astrometrically detectable if the star was fainter than K=14 mag and thus located at the required minimum distance or beyond.

search for astrometric reference stars.

The numbers presented in this section make it clear that the final target selection will be dominated by the availability of suitable reference stars, and that a large number of targets will have to be searched to find the ones with suitable reference stars.

5. PREPARATORY OBSERVATIONS

In order to better characterize the target stars themselves, already known potential reference stars in these fields as well as to identify potential hitherto unknown reference stars not listed in the searched catalogs, we plan to perform preparatory observations of all our fields. As a first step, we plan to acquire near-infrared photometry, especially K magnitudes, for all our target and reference stars. The images might also be used to identify close visual double stars (among targets as well as references) that might corrupt the astrometric measurements. In a next step, we probably need to take spectra to characterize all the stars that are going to be observed; the spectra might be required to accurately correct for differential chromatic refraction, and they can also be used to obtain an indication on the chromospheric activity of the star.

In order to assess the suitability of a given reference star, it would be advantageous to measure precise radial velocities to ensure that the star has no companions that could eventually impact the astrometry. However, this is not feasible for such a large sample on a timescale of only a few years. Instead, we have to rely on more indirect methods. Either we have to acquire radial velocities which are not precise enough to detect virtually all companions that render the reference star unsuitable, or we have to take adaptive optics images of the reference stars to identify potentially disturbing components. Radial velocities however would be better suited to the task, since it is especially the short period companions that cause an observable effect over the duration of the project. The curvature caused by companions with very long periods (as compared the project duration of a few years) might not be detected curing the course of a relatively short astrometric survey.

At certain distances, planets orbiting around reference stars can also be a concern. However, this can be alleviated by using only stars for which a giant planet could not be detected with 10μas astrometric accuracy. Using the mass and color calibrations by Baraffe et al.[17], we calculated the minimum distance at which a main-sequence star of given $V - K$ color would have to be located so that a companion with 1 M_J in a 5 year orbit would not be detectable with 10μas astrometric accuracy. Assuming that the star is on the main sequence, we then converted this minimum distance into a minimum apparent magnitude in K that the star was allowed to have if its putative companion should not show up in the astrometry. These K magnitudes are shown in Fig. 4 as a function of $V - K$ color. For example, all M0 stars ($V - K \approx 3.7$ mag) fainter than K=14 mag should not suffer from astrometric jitter induced by planetary companions. If the star is not on the main sequence but evolved into the giant region in the Hertzsprung-Russell diagram, its distance at a given apparent magnitude is even larger than the minimum required distance and is also safe to use as a reference stars in terms of astrometric noise caused by planetary companions.

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