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Precise radial velocities of giant stars

IV. A correlation between surface gravity and radial velocity variation and a statistical investigation of companion properties*

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ABSTRACT

Context. Since 1999, we have been conducting a radial velocity survey of 179 K giants using the Coudé Auxiliary Telescope at UCO/Lick observatory. At present ~20−100 measurements have been collected per star with a precision of 5 to 8 m s^{-1}. Of the stars monitored, 145 (80%) show radial velocity (RV) variations at a level >20 m s^{-1}, of which 43 exhibit significant periodicities.
Aims. Our aim is to investigate possible mechanism(s) that cause these observed RV variations. We intend to test whether these variations are intrinsic in nature, or possibly induced by companions, or both. In addition, we aim to characterise the parameters of these companions.
Methods. A relation between $\log g$ and the amplitude of the RV variations is investigated for all stars in the sample. Furthermore, the hypothesis that all periodic RV variations are caused by companions is investigated by comparing their inferred orbital statistics with the statistics of companions around main sequence F, G, and K dwarfs.
Results. A strong relation is found between the amplitude of the RV variations and $\log g$ in K giant stars, as suggested earlier by Hatzes & Cochran (1998). However, most of the stars exhibiting periodic variations are located above this relation. These RV variations can be split in a periodic component which is not correlated with $\log g$ and a random residual part which *does* correlate with $\log g$. Compared to main-sequence dwarf stars, K giants frequently exhibit periodic RV variations. Interpreting these RV variations as being caused by companions, the orbital parameters are different from the companions orbiting dwarfs.
Conclusions. Intrinsic mechanisms play an important role in producing RV variations in K giants stars, as suggested by their dependence on $\log g$. However, it appears that periodic RV variations are *additional* to these intrinsic variations, consistent with them being caused by companions. If indeed the majority of the periodic RV variations in K giants is interpreted as due to substellar companions, then massive planets are significantly more common around K giants than around F, G, K main-sequence stars.

Key words. stars: variables: general – techniques: radial velocities – line: profiles

1. Introduction

For more than a decade, radial velocity observations with accuracies of order m s^{-1} have been within reach (see for instance Marcy & Butler 2000; and Queloz et al. 2001). Even accuracies of less than 1 m s^{-1} (Pepe et al. 2003) are possible now. With these observations, more than 200 sub-stellar companions have been discovered by measuring the reflex motions of their parent stars. Most of these sub-stellar companions have been detected around F, G and K main sequence stars, but detections around an A star (Galland et al. 2006) and several subgiants (Johnson et al. 2006, 2007) have also been reported recently. Moreover, 10 giant stars were reported to have sub-stellar companions (ι Draconis (K2III) Frink et al. 2002; HD 104985 (G9III) Sato et al. 2003; HD 47526 (K1III) Setiawan et al. 2003; HD 13189 (K2II-III) Hatzes et al. 2005; HD 11977 (G5III) Setiawan et al. 2005; Pollux (K0III) Hatzes et al. 2006; Reffert et al. 2006; 4UMa (K1III) Döllinger et al. 2007, NGC 2423 No. 3 and NGC 4349 No. 127 Lovis & Mayor 2007; and recently HD 17092 (K0III) Niedzielski et al. 2007)[1]. In addition to searches for extra-solar companions, radial velocity observations prove to be very useful for detecting solar-like oscillations in stars with turbulent atmospheres, such as the dwarf α Cen A (e.g. Bedding et al. 2006), the subgiant Procyon (e.g. Eggenberger et al. 2004: Martić et al. 2004) and the giant ϵ Ophiuchi (e.g. De Ridder et al. 2006).

With techniques for accurate radial velocity observations at hand, a survey was started in 1999 to verify whether K giants are stable enough to be used as astrometric reference stars for SIM/PlanetQuest (Space Interferometry Mission) (Frink et al. 2001). This survey contains 179 stars and uses the Coudé Auxiliary Telescope (CAT) at University of California Observatories / Lick Observatory, in conjunction with the Hamilton Echelle Spectrograph. The survey has recently been expanded to about 380 giants and is still ongoing. For the

* Based on data obtained at UCO/Lick Observatory, USA.

[1] For updated information on sub-stellar companions, see http://exoplanet.eu and http://exoplanets.org

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analysis described in the present paper only data from the initial 179 stars are used.

From this survey, companions have been announced for ι Draconis (Frink et al. 2002) and Pollux (Reffert et al. 2006). Stars with radial velocity variations of less than 20 m s^{-1} have been presented as stable stars by Hekker et al. (2006). In addition, some binaries discovered with this survey, as well as an extensive overview of the sample, will be presented in forthcoming papers.

As almost all of the stars show significant radial velocity variations, we investigate here which mechanism causes these variations. Non-periodic radial velocity variations, of the order of the investigated timescales, are most likely caused by some intrinsic mechanism, while the periodic variability can also be caused by companions. We also investigate the characteristics of these companions.

In Sect. 2, the radial velocity observations are described in detail. In Sect. 3, the relation between the observed radial velocity amplitude and surface gravity is investigated. In Sect. 4, we explore the hypothesis that all periodic radial velocity variations are caused by sub-stellar companions, and we compare the inferred orbital parameters with those obtained for sub-stellar companions orbiting main sequence stars. Our conclusions are presented in Sect. 5.

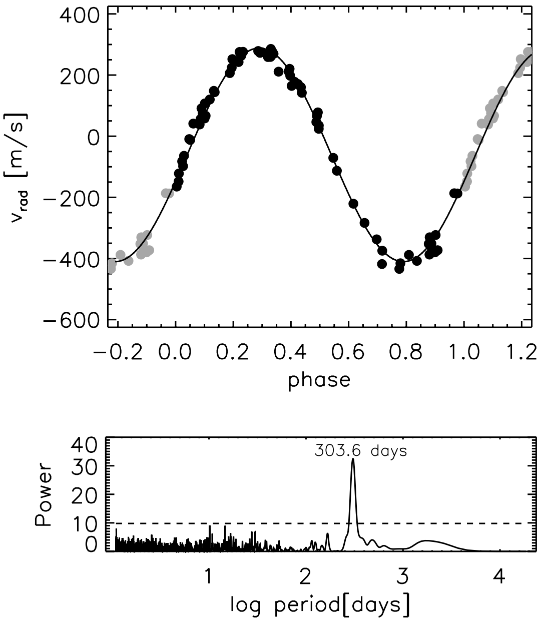

Fig. 1. Radial velocity variations as a function of phase for a star (HIP 34693) with a highly significant period (*top*), with its periodogram (*bottom*). The dashed line in the periodogram indicates the significance threshold.

2. Radial velocity variations

The initial 179 stars selected for the radial velocity survey are used in the present work. These stars have been selected from the Hipparcos catalogue (Perryman & ESA 1997), based on the criteria described by Frink et al. (2001). The selected stars are all brighter than 6 mag, are presumably single and have photometric variations <0.06 mag in V. The survey started in 1999 at Lick Observatory using the Coudé Auxiliary Telescope (CAT) in conjunction with the Hamilton Echelle Spectrograph (R = 60 000). The system with an iodine cell in the light path has been described by Marcy & Butler (1992) and Valenti et al. (1995). With integration times of up to thirty minutes for the faintest stars (m_v = 6 mag) we reach a signal to noise ratio of about 80–100 at λ = 5500 Å, yielding a radial velocity precision of 5–8 m s^{-1}. As we are looking for radial velocity variations of order 10 to 100 m s^{-1}, this is adequate and hence no attempt has been made to reach the 3 m s^{-1} accuracy which is in principle possible with this setup (Butler et al. 1996). For the determination of the radial velocities the pipeline described by Butler et al. (1996) is used. In this pipeline, a template iodine spectrum and a template spectrum of the target star obtained without an iodine cell in the lightpath are used to model the stellar observations with a superposed iodine spectrum. The Doppler shift is a free parameter in this model. Note that with this method the absolute radial velocity is not measured, but the radial velocity relative to the stellar template is obtained.

All 179 stars are subjected to a period search. The periodicity of the radial velocity variations is determined first of all from a classical Lomb-Scargle (LS) periodogram (Scargle 1982). The significance threshold is set to 6σ, where the noise level is determined from the average power of the residual Scargle periodogram for frequencies between 0 and 0.03 cycles per day (c/d) (0.35 μHz) and a frequency step of 0.00001 c/d (0.12 × 10^{-3} μHz). We adopted the conventional method of iterative sinewave fitting ("prewhitening") to search for subsequent frequencies (Kuschnig et al. 1997). In Figs. 1 and 2, the radial velocity variation as a function of phase is shown for two stars. The period of the star in Fig. 1 is highly significant, while the one in Fig. 2 is close to the significance threshold. Periodograms are shown in the bottom panels of these figures. As properly emphasized by Cumming et al. (1999), such a classical period search may not be appropriate for unevenly spaced sparse data, even though we set the significance level at a conservatively high level. In order to check this, we have done an additional LS analysis after prewhitening the original data by a linear polynomial. This led almost always to the same frequencies. We only accepted a frequency when it was found to meet the significance criterion for both these analyses. The significant frequencies are listed in Table 1.

3. Radial velocity amplitude – surface gravity relation

Hatzes & Cochran (1998) already investigated the origin of the observed radial velocities in K giant stars. Although their sample contained only 9 stars, they suggested that the amplitude of the radial velocity increases with decreasing surface gravity (log g). In lower surface gravity it takes longer to decrease the velocity of a moving parcel which results in larger amplitudes and the relation suggested by Hatzes & Cochran (1998) would therefore be evidence for pulsations or rotational modulation as the mechanism for these long period radial velocity variations.

For the present sample, log g values were determined spectroscopically by Hekker & Meléndez (2007), by imposing excitation and ionisation equilibrium of iron lines through stellar models. The equivalent width of about two dozen carefully selected iron lines were used for a spectroscopic LTE analysis based on the 2002 version of MOOG (Sneden 1973) and Kurucz model atmospheres which include overshooting (Castelli et al. 1997). These authors estimated the error on log g to be 0.22 dex from the scatter found in a comparison with literature values. A detailed description of the stellar parameters for individual stars and a comparison with literature values are available in Hekker & Meléndez (2007) and is therefore omitted here.

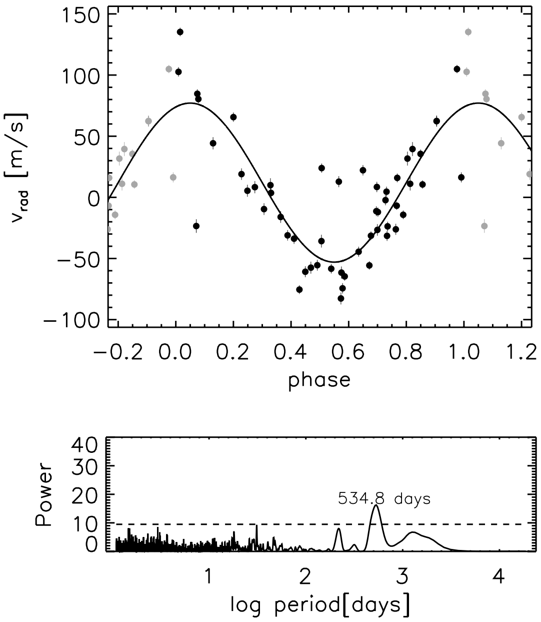

Fig. 2. Radial velocity variations as a function of phase for a star (HIP 7607) with a period close to the significance threshold (*top*), with its periodogram (*bottom*). The dashed line in the periodogram indicates the significance threshold.

Table 1. Single stars with significant frequencies.

Star	Frequency μHz	Period days	Frequency μHz	Period days
HIP 3419	0.0638	181	0.1197	97
HIP 7607	0.0216	536		
HIP 7884	0.0184	629		
HIP 13905	0.0223	519		
HIP 16335	0.0197	588		
HIP 19011	0.0252	459		
HIP 21421	0.0203	570	0.0448	237
HIP 23015	0.0151	767	0.0073	1586
HIP 23123	0.0135	857		
HIP 31592	0.0144	804		
HIP 33160	0.0226	512		
HIP 34693	0.0380	305		
HIP 36616	0.0033	3507	0.0389	298
HIP 37826	0.0194	597		
HIP 38253	0.0171	677		
HIP 39177	0.0133	870		
HIP 40526	0.0172	673		
HIP 46390	0.0233	497		
HIP 47959	0.0187	619		
HIP 53229	0.0022	5261		
HIP 53261	0.0149	777		
HIP 57399	0.0196	591		
HIP 64823	0.0021	5512		
HIP 69673	0.0382	303	0.0187	619
HIP 73133	0.0014	8267	0.0157	737
HIP 73620	0.0226	512		
HIP 74732	0.0233	497		
HIP 75458	0.0226	512		
HIP 79540	0.0203	570		
HIP 80693	0.0022	5261	0.0198	585
HIP 84671	0.0251	461		
HIP 85139	0.2895	40		
HIP 85355	0.0258	449	0.0056	2067
HIP 85693	0.0175	661		
HIP 87808	0.0153	757		
HIP 88048	0.0218	531	0.0029	3991
HIP 91117	0.0303	382		
HIP 109023	0.0199	582		
HIP 109492	0.0217	533		
HIP 109602	0.0130	890		
HIP 109754	0.0189	612		
HIP 113562	0.0401	289	0.0472	245
HIP 114855	0.0639	181		

In Fig. 3, we show half of the peak-to-peak value of the observed radial velocity variations as a function of $\log g$ for K giants in our sample. A clear trend is visible between increasing radial velocity variations in single stars, and decreasing $\log g$, which provides a strong indication that, at least for a large fraction of stars in our sample, the observed radial velocity variations are induced by a mechanism intrinsic to the star. This trend is present for stars with random as well as stars with periodic radial velocity variations. Also, nearly all stars with periodic radial velocity variations and $\log g \geq 1.6$ are located above the fit in Fig. 3. Seven single stars have a higher radial velocity variation than expected based on their $\log g$ value, i.e. they are situated more than 3.5σ above the best fit for the relation obtained for single stars. These stars are indicated with arrows in Fig. 3. The radial velocity variation observed for HIP 53229 may be due to a stellar companion in a wide orbit, with a period much longer than the observation time span. Due to this long period the companion mass, and, therefore, the (sub-)stellar nature, is still very uncertain. HIP 33152 is classified as a supergiant. The observed radial velocity variations for HIP 80693, HIP 36616, and HIP 88048 can be fitted with two Keplerian orbits, while HIP 75458 can be explained by an eccentric sub-stellar companion (Frink et al. 2002) and an additional linear trend, indicating a companion in a wide orbit. HIP 34693 can be fitted very accurately with a Keplerian orbit of a single nearly sinusoidal sub-stellar companion.

In order to investigate the simultaneous occurrence of substellar companions and oscillations in giants, the best Keplerian fits are subtracted from the observed radial velocity variations of both the binaries and the single stars with significant periodic radial velocity variations. The half peak-to-peak values of these residuals are plotted as a function of surface gravity in Fig. 4, also showing the linear fit through the non-periodic stars, and the amplitudes of the subtracted periodic signals. There are several interesting points to make about this graph. Firstly, almost all periodic stars show larger radial velocity variations than predicted by the relation found for non-periodic stars, but when the periodicities are removed, their residual radial velocity variations follow the same relation as found for the non-periodic stars. This could be interpreted as evidence for both intrinsic (non-periodic radial velocity variation) and extrinsic (periodic variations) mechanisms playing a role in these stars. Secondly, there is no correlation between the amplitude of the subtracted periodic signal and $\log g$, which provides additional evidence for the presence of companions. Thirdly, almost all (8 out of 9) stars with $\log g \leq 1.6$ exhibit periodic variations. If these indeed have an extrinsic mechanism, it would mean that ~90% of these stars have sub-stellar companions. However, from an astrophysical point of view, stars with such low surface gravities are already very high on the giant branch or even on the asymptotic giant branch. At these low gravities, stars cannot be constant anymore, as the outer layers are so diluted that instabilities occur easily, either periodic or random. Stated differently, these stars are very close to the semi-regulars, which are on their way to become Mira variables. Hence, these periodic variations could well be intrinsic.

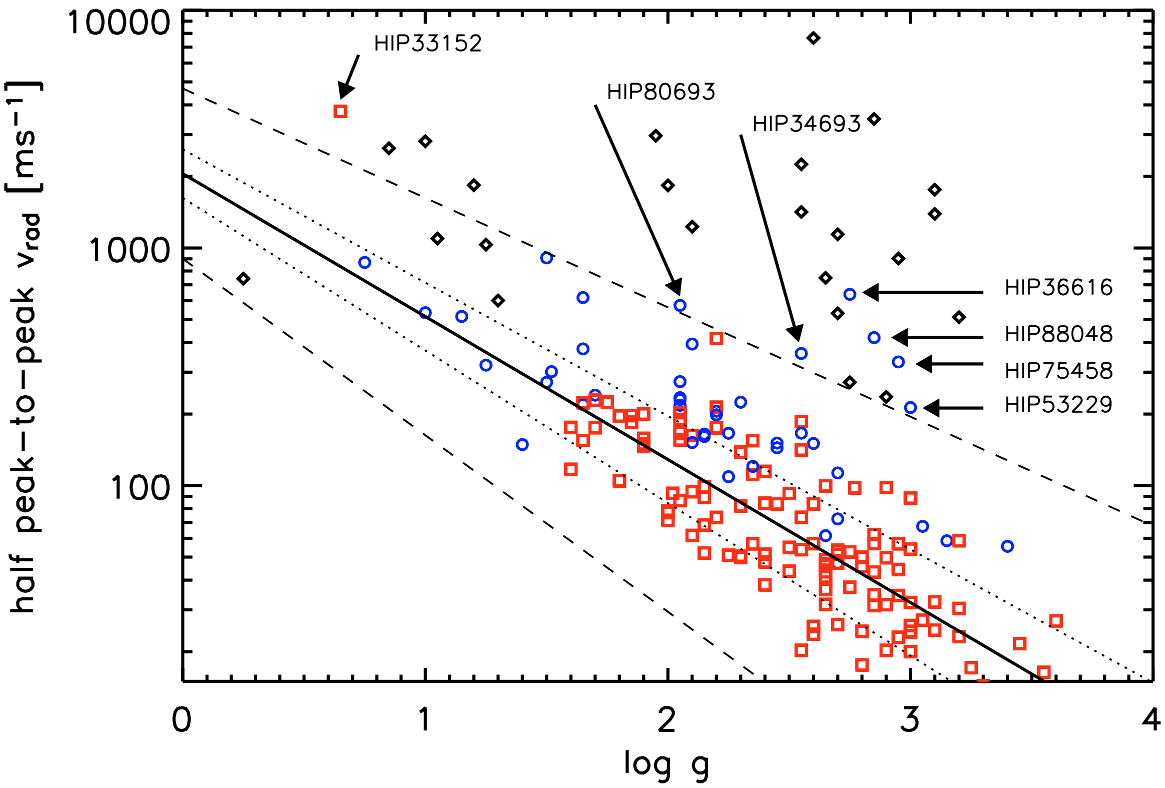

Fig. 3. Half of the peak-to-peak variation of the radial velocity as a function of surface gravity ($\log g$). The blue ∘ indicate the single stars with periodic radial velocity variations (see text for periodicity criteria), the red □ indicate single stars with random radial velocity variations, and stellar binaries (companion mass $>100\ M_{\rm Jup}$) are indicated with black ⋄ symbols. (Colours are only visible in the online version of the paper.) The solid line is the best fit through the random single stars, the dotted line indicates the 1σ interval around the best fit and the dashed line indicates the 3.5σ interval. Single stars with a higher radial velocity amplitude than expected based on their $\log g$ value (more than 3.5σ above the best fit) are indicated by arrows. Six of the 8 stars with periodic radial velocity variations and $\log g < 1.6$ are classified bright giants or supergiants (Perryman & ESA 1997).

4. Companion interpretation

From the analysis of the correlation between radial velocity amplitude and surface gravity we have evidence for the presence of both intrinsic variability and companions in at least a fraction of the K giant stars with periodic radial velocity variations. In order to study the characteristics of these companions, we take the hypothesis that the periodic radial velocity variations detected in 43 of our K giant stars, excluding binaries, are caused by sub-stellar companions. Under this hypothesis, we investigate the statistical properties of the orbital parameters of the sample and compare these with the statistical properties of companions orbiting F, G and K dwarfs.

According to our analysis, 55 stars in the sample would have a single companion, and 11 stars multiple companions. Twenty-three (22 single and 1 in a multiple system) of these companions have $m \sin i$ larger than 100 $M_{\rm Jup}$ and should be interpreted as stellar binaries. By advancing the multiple sub-stellar systems forward in time via a Runga-Kutta integration, we investigated the stability of the systems, taking into account the mutual interactions of the companions. With the orbital parameters that minimise χ^2 taken at face value, we found that most of the inferred sub-stellar multiple systems would be "likely unstable", with a change in semi-major axis >1% and <10%, or "unstable" with a change in semi-major axis >10% on a time scale of 100 years due to companion-companion interaction.

However, the inferred stability depends on the starting epoch of the computations, as well as on the orbital parameters, which might change with an increasing number of observations. Furthermore, there is no guarantee that the obtained χ^2 minimum is a global minimum. Therefore, stars with multiple inferred sub-stellar companions that seem to be unstable, might also have stable solutions. One could also use the equations for dynamical stability described by Gladman (1993) and Marcy et al. (2001). Gladman (1993) also notes that the Hill stability criteria for companions in initially eccentric orbits may not be met, but that the systems may still be found to be empirically quite stable for a long period of time. In order to draw a firm conclusion on the stability of a particular system, a more thorough investigation is needed, as well as data with a longer time base, which is beyond the scope of this paper.

For all stars with periodic radial velocity variations, we checked the Hipparcos (Perryman & ESA 1997) photometry. We checked periodograms for significant frequencies close to the obtained radial velocity period, and plotted the photometric values phased with the radial velocity period. None of the stars show photometric variations related to the observed radial velocity variations.

The mass distribution of our K giant sample is not known very well. The stellar masses are typically between 1 and 4 $M_\odot$. Hence most of their main sequence progenitors should have been of A or F spectral class. The distribution of orbital parameters of sub-stellar companions orbiting A and F main sequence stars is still unknown. The core accretion model predicts more giant planets around more massive stars, so that the distribution of orbital parameters of sub-stellar companions

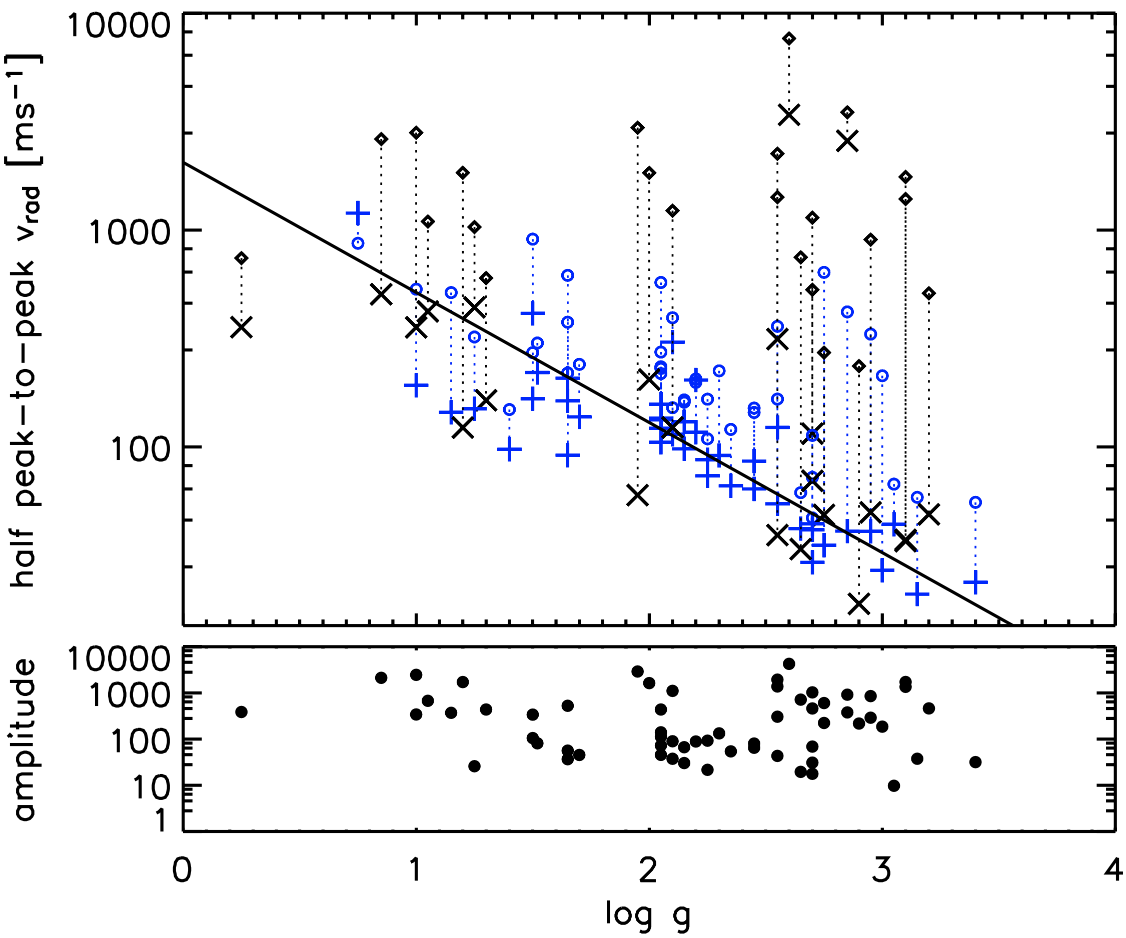

Fig. 4. *Top*: half of the peak-to-peak variation of the radial velocity as a function of surface gravity (log g), as in Fig. 3, but showing only those stars with periodic radial velocity variations (blue ∘) and stellar binaries (black ⋄). The blue + and black × symbols indicate the amplitude of the radial velocity variations for these stars after subtraction of the Keplerian fits. (Colours are only visible in the online version of the paper.) The solid line indicates the linear fit through the stars with non-periodic radial velocity variations (from Fig. 3). *Bottom*: amplitudes of the subtracted Keplerian fits as a function of log g.

orbiting F, G and K main-sequence stars probably cannot serve as a proxy. However, it should be instructive to compare the two distributions.

Since the data presented here span ~2500 days, radial velocity variations with longer periods are uncertain, and, therefore, not taken into consideration. Companions with periods exceeding the observation time span are also excluded from the F, G, and K main sequence star statistics.

4.1. Mass distribution

Figure 5 shows the distribution of inferred companion masses of our K giant sample. First, notice that 30% of the inferred companions would have masses in the brown dwarf regime 15 $M_{\rm Jup} < m \sin i < 80$ $M_{\rm Jup}$. This is in sharp contrast to the brown dwarf statistics around F, G and K main sequence stars for which only very few companions are found with $m \sin i >$ 15 $M_{\rm Jup}$ around more than thousand stars. This is known as the brown dwarf desert and is possibly caused by migration and merging of brown dwarfs in a viscous disk with a mass at least comparable to the brown dwarf mass (Armitage & Bonnell 2002).

The dashed line in Fig. 5 indicates the rise of sub-stellar companion masses $M^{-1.05}$ from 10 $M_{\rm Jup}$ down to Saturn masses for main sequence stars (Marcy et al. 2005), normalised to

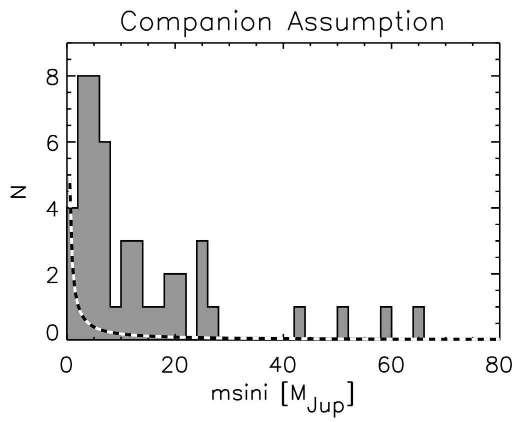

Fig. 5. A histogram of $m \sin i$ of inferred companion masses orbiting K giants in our sample. The dashed line indicates the rise of planet masses $M^{-1.05}$ from 10 $M_{\rm Jup}$ down to Saturn masses for sub-stellar companions around main sequence stars (Marcy et al. 2005), normalised to the number of stars in our sample.

the number of stars in our sample. We use a two-sided Kolmogorov-Smirnov test (Press et al. 1992) (hereafter KS-test) to compare the $M^{-1.05}$ fit and the mass distribution ($m \sin i <$ 80 $M_{\rm Jup}$) of our sample and find a probability of 0.05% (0.002%

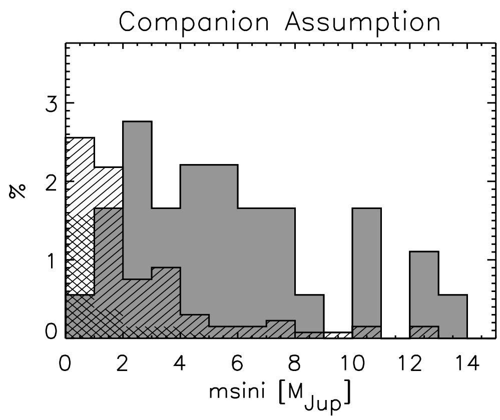

Fig. 6. Zoom in on the low end of the companion mass distribution of inferred sub-stellar companions orbiting K giant stars in our survey, shown as percentage of the total number of stars in the sample (gray histogram). The hatched histogram shows the distribution of companion masses orbiting main sequence stars as shown in Fig. 1 of Marcy et al. (2005), as a percentage of the total number of stars in their sample. The cross hatched area are main sequence stars with companions at a semi-major axis smaller than 0.3 AU (see Fig. 7).

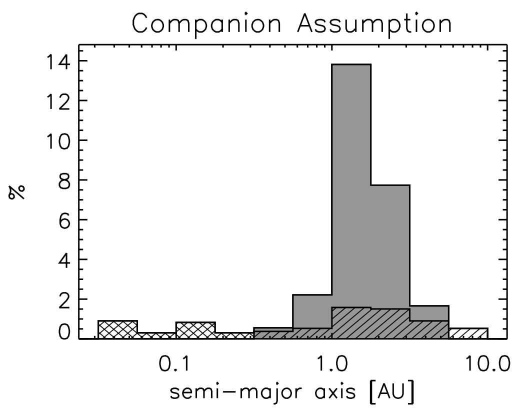

Fig. 7. Semi-major axis distribution of inferred K giant companions in our sample (gray histogram), shown as a percentage of the total number of stars in the sample. The hatched histogram shows the distribution for F, G and K main sequence stars as shown in Fig. 2 of Marcy et al. (2005), as a percentage of the total number of stars in their sample. The main sequence stars with a companion orbiting at a semi-major axis smaller than 0.3 AU are cross-hatched. These are also indicated in Figs. 6 and 8.

for $m \sin i < 28$ $M_{\rm Jup}$) that these are identical. This implies that inferred sub-stellar companions around K giants in our sample have higher masses compared to companions around F, G and K main sequence stars.

Figure 6 shows the low-mass companion distribution of our survey. Most K giant companions would have inferred masses between 2 and 8 $M_{\rm Jup}$, while the fraction of companions orbiting F, G and K dwarfs strongly decreases with increasing $m \sin i$.

4.2. Semi-major axis distribution

The distribution of the companions' semi-major axis is shown in Fig. 7. No inferred companions with semi-major axis smaller than 0.3 AU are present in the K giant sample, possibly due to increased stellar radii of giants. The fraction of stars with an inferred companion with a semi-major axis between 1 and 3 AU is much higher among the K giants compared to the F, G and K dwarfs. A comparison between the two distributions with a KS-test reveals a probability for the two distributions to be identical of 11%. This increases to 32% when omitting the main sequence stars with semi-major axis <0.3 AU. The increasing incompleteness beyond 3 AU, due to the limited time span of surveys, is present in both samples as the surveys cover a comparable amount of time. This incompleteness cannot cause the significant difference in the peak between 1 and 3 AU.

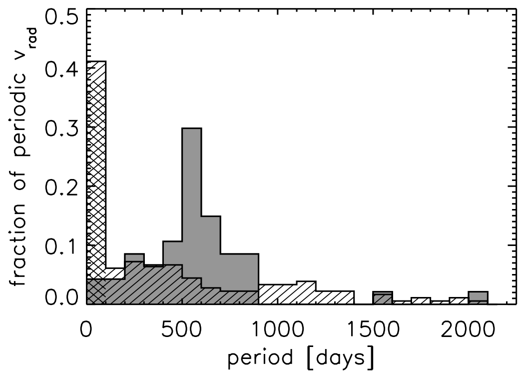

Fig. 8. Period distribution of the observed radial velocity variations shown as a fraction of all significant periods (gray histogram). The period distribution of main sequence stars (Butler et al. 2006) is shown in the hatched histogram, as a fraction of the total number of observed companions. The cross hatched area are main sequence stars with a semi-major axis smaller than 0.3 AU (see Fig. 7).

4.3. Period distribution

In Fig. 8 the period distribution of the observed radial velocity variations is shown and compared with the companion period distribution of dwarfs. The large fraction of F, G and K dwarf companions with orbital periods shorter than 100 days corresponds to the ones with semi-major axis smaller than approximately 0.3 AU. The close-in short-period companions are not present around K giants, while about 80% of these stars with observed radial velocities have periods ranging between 400 and 800 days. A KS-test reveals a probability of less than 0.0001% for the two distributions to be identical. The probability remains below this level, when the companions orbiting main sequence stars with a semi-major axis <0.3 AU are omitted.

4.4. Eccentricity distribution

Figure 9 shows the distribution of companion eccentricities for K giants in our sample and for dwarfs. Companions of dwarfs with periods less than 20 days are excluded, as these might be tidally circularised. The fraction of companion eccentricities <0.3 for the giants is 75% compared to 50% for companions orbiting F, G and K dwarfs. The KS-test shows that these distributions are nearly identical (97%).

4.5. Iron abundance

Companion occurrence correlates strongly with the abundance of heavy elements (see for instance Gonzalez 1997; Fischer & Valenti 2005; and Santos et al. 2005), such that F, G, and K dwarf stars with supersolar abundance are more likely to harbour sub-stellar companions (about 50% of the stars with $0.3 <$ [Fe/H] < 0.5). The increase of the fraction of F, G and K dwarfs harbouring companions with increasing metallicity is well fitted

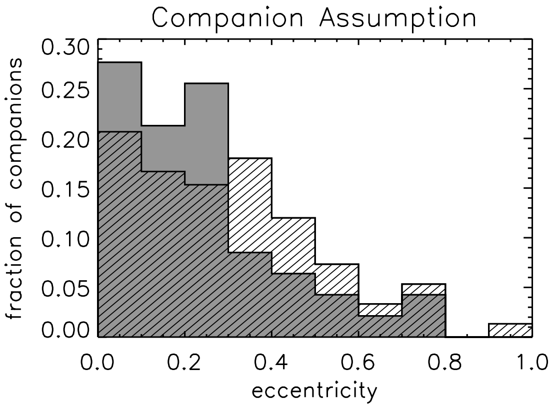

Fig. 9. Distribution of eccentricities for possible companions around K giants in our sample (gray histogram) shown as a fraction of all possible sub-stellar companions in the sample. The hatched histogram is the eccentricity distribution of companions around main sequence stars (Butler et al. 2006) shown as a fraction of all companions around main sequence stars. Companions with periods shorter than 20 days are excluded from the latter sample as these might be tidally circularised.

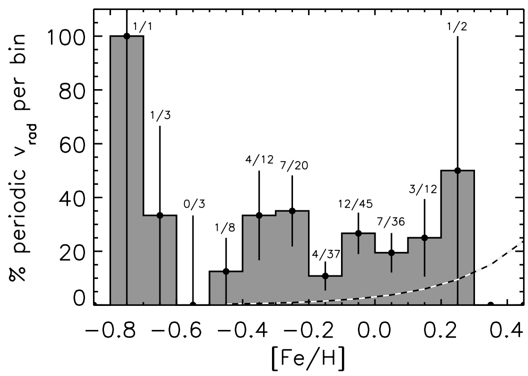

Fig. 10. Iron abundance [Fe/H] distribution of K giant stars with periodic radial velocity variations shown as a percentage of the total number of observed stars with iron abundance in the same interval. The numbers above each bar on the histogram indicate the ratio of stars with a significant periodic radial velocity variation to the total number of stars in each bin. The error bars are calculated assuming Poisson statistics (i.e., the percentage of stars with periodic radial velocities divided by the square root of the number of stars with periodic radial velocities). The dashed line is the power law derived for the increasing trend in the fraction of stars with companions as a function of metallicity of F, G and K main sequence stars (Fischer & Valenti 2005).

with a power law, yielding a probability for such a star to harbour a companion to be: $P = 0.03 \cdot [(N_{\rm Fe}/N_{\rm H})/(N_{\rm Fe}/N_{\rm H})_{\odot}]^{2.0}$ (Fischer & Valenti 2005).

In Fig. 10 the iron abundance distribution of stars with periodic radial velocity variations is shown as a percentage of the total number of observed stars with iron abundance in the same interval. The iron abundance is determined spectroscopically by imposing excitation and ionisation equilibrium in iron lines and is described by Hekker & Meléndez (2007). The maximum iron abundance of a K giant star in our sample is 0.29 and, therefore, we do not probe the high metallicity region in which F, G and K dwarfs are most likely to harbour a companion.

The mean metallicity of the K giants in the entire sample is −0.12 dex, while the mean metallicity of the stars with periodic radial velocity variations, presented in Fig. 10, is −0.13 dex. No correlation between companion occurrence and abundance, similar to the one which is present for dwarf stars, is found in this sample of giant stars.

5. Discussion and conclusion

The tight correlation we found between $\log g$ and half of the peak-to-peak radial velocity variations seems to indicate that a large fraction of the observed radial velocity variations in our sample of K giants is induced by mechanism(s) intrinsic to the stars. We also present evidence that both intrinsic and extrinsic mechanisms play a role. The stars with a significant periodic signal are almost all located above the radial velocity amplitude vs. $\log g$ relation, but when the periodic signal is removed, the residuals show the same trend as for the non-periodic stars. Furthermore, no correlation is present between the amplitude of the periodic signal and $\log g$.

Almost all of the lowest $\log g$ stars show periodic variations. It may be possible that stars with such low surface gravity cannot be constant and that in these dilute atmospheres instabilities can occur very easily, and therefore may be periodic, but not extrinsic.

Based on the evidence that extrinsic mechanism(s) play a role for K giant stars with periodic radial velocity variations we investigated the hypothesis that this periodic signal is caused by the reflex motion of sub-stellar companions orbiting these stars. We presented the characteristics of the orbital parameters of these companions and compared them with the known orbital parameters of sub-stellar companions orbiting F, G and K dwarfs.

About 25% of the stars in our sample have radial velocity variations with significant periodicity, and could possibly harbour a sub-stellar companion, while approximately only 8% of the 1330 F, G and K main sequence stars investigated by Marcy et al. (2005) have a sub-stellar companion. Recently Johnson et al. (2007) and Lovis & Mayor (2007) showed that the number of companion harbouring stars increases with mass. The giants in the present sample have typical masses between 1 and 4 $M_{\odot}$ and are in general more massive than the main sequence stars investigated for companions. So, the high percentage is qualitatively in agreement with the results from the literature. Furthermore, Lovis & Mayor (2007) suggest that more massive stars form more massive planetary systems than lower mass stars. Figures 5 and 6 show that we find, in general, more massive companions around the more massive K giants than are present around F, G and K dwarfs.

The high percentage of more massive companions around the more massive K giant stars would also be compatible with the core accretion model. This model predicts very few giant planets, but a relatively large number of planets with the mass of Neptune or smaller around M dwarfs (Laughlin et al. 2004; Ida & Lin 2005). This is mainly the result of a much reduced surface density of the disk and the resulting shorter disk evolution timescales compared to those for more massive stars, implying that planet properties vary with the mass of their host stars. In particular, one would expect more sub-stellar companions with higher masses in our giant sample, as is indeed the case if we assume that the companion hypothesis is correct.

The mean metallicity of companion-hosting K giants would be similar to the mean metallicity of the total sample. This is in contrast with the correlation between companion occurrence and metallicity present in F, G and K dwarfs (e.g. Fischer & Valenti 2005). So far, several groups have investigated the correlation between companion occurrence and metallicity for giants with different results. Sadakane et al. (2005) and Pasquini et al. (2007) agree that companion-hosting giants are on average not metal-rich, while Hekker & Meléndez (2007) find that giants with announced companions have higher metallicities than their total sample of giants. A detailed discussion about these different results is presented by Hekker & Meléndez (2007). They conclude that the samples on which the results are based are slightly different and the more metal-rich stars used in their study are lacking in the study by Pasquini et al. (2007). Furthermore, there is a difference in zero-point correction for the metallicities of announced companion-hosting stars from different surveys. All in all, these inferences are based on small-number statistics and all results have to be taken with caution.

The larger semi-major axis and long periods of the inferred companions orbiting K giant stars compared to companions orbiting dwarf stars are most likely due to the extended atmospheres of K giants. For the eccentricity no significant difference is found in the distribution between companions orbiting dwarfs or giants. Nevertheless, the high number of inferred companions around giants with eccentricities <0.3 is striking. One could suspect that companion orbits circularise over time and that the companions in circular orbits are older than the eccentric ones, but there is no evidence for this hypothesis.

In principle, nearly sinusoidal radial velocity variations could also be caused by pulsations or spots. Although the periods of the radial velocity variations could well be the rotational periods of the stars, the presence of prominent spots is not very likely. In that case one would also expect photometric variations with periods correlated with the radial velocity variations. From the Hipparcos photometry (Perryman & ESA 1997) such correlations were not found.

In order to distinguish with certainty between companions and pulsations as the cause of the observed radial velocity variations, one needs to perform a spectral line profile analysis. A technique for doing this with very high-resolution spectra ($R \geq 100\,000$) will be presented separately (Hekker et al., in preparation) because the amount of such data at hand today is insufficient to add significantly to the conclusions of this paper.

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References

Armitage, P. J., & Bonnell, I. A. 2002, MNRAS, 330, L11
Bedding, T. R., Butler, R. P., Carrier, F., et al. 2006, ApJ, 647, 558
Butler, R. P., Marcy, G. W., Williams, E., et al. 1996, PASP, 108, 500
Butler, R. P., Wright, J. T., Marcy, G. W., et al. 2006, ApJ, 646, 505
Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, A&A, 324, 432
Cumming, A., Marcy, G. W., & Butler, R. P. 1999, ApJ, 526, 890
De Ridder, J., Barban, C., Carrier, F., et al. 2006, A&A, 448, 689
Döllinger, M. P., Hatzes, A. P., Pasquini, L., et al. 2007, A&A, 472, 649
Eggenberger, P., Carrier, F., Bouchy, F., & Blecha, A. 2004, A&A, 422, 247
Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102
Frink, S., Quirrenbach, A., Fischer, D., Röser, S., & Schilbach, E. 2001, PASP, 113, 173
Frink, S., Mitchell, D. S., Quirrenbach, A., et al. 2002, ApJ, 576, 478
Galland, F., Lagrange, A.-M., Udry, S., et al. 2006, A&A, 452, 709
Gladman, B. 1993, Icarus, 106, 247
Gonzalez, G. 1997, MNRAS, 285, 403
Hatzes, A. P., & Cochran, W. D. 1998, in Cool Stars, Stellar Systems, and the Sun, ed. R. A. Donahue, & J. A. Bookbinder, ASP Conf. Ser., 154, 311
Hatzes, A. P., Guenther, E. W., Endl, M., et al. 2005, A&A, 437, 743
Hatzes, A. P., Cochran, W. D., Endl, M., et al. 2006, A&A, 457, 335
Hekker, S., & Meléndez, J. 2007, A&A, 475, 1003
Hekker, S., Reffert, S., Quirrenbach, A., et al. 2006, A&A, 454, 943
Ida, S., & Lin, D. N. C. 2005, ApJ, 626, 1045
Johnson, J. A., Marcy, G. W., Fischer, D. A., et al. 2006, ApJ, 652, 1724
Johnson, J. A., Fischer, D. A., Marcy, G. W., et al. 2007, ApJ, 665, 785
Kuschnig, R., Weiss, W. W., Gruber, R., Bely, P. Y., & Jenkner, H. 1997, A&A, 328, 544
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, ApJ, 612, L73
Lovis, C., & Mayor, M. 2007, A&A, 706, in press
Marcy, G., Butler, R. P., Fischer, D., et al. 2005, Progr. Theor. Phys. Suppl., 158, 24
Marcy, G. W., & Butler, R. P. 1992, PASP, 104, 270
Marcy, G. W., & Butler, R. P. 2000, PASP, 112, 137
Marcy, G. W., Butler, R. P., Vogt, S. S., et al. 2001, ApJ, 555, 418
Martić, M., Lebrun, J.-C., Appourchaux, T., & Korzennik, S. G. 2004, A&A, 418, 295
Niedzielski, A., Konacki, M., Wolszczan, A., et al. 2007, ApJ, 669, 1354
Pasquini, L., Döllinger, M. P., Weiss, A., et al. 2007, A&A, 473, 979
Pepe, F., Bouchy, F., Queloz, D., & Mayor, M. 2003, in Scientific Frontiers in Research on Extrasolar Planets, ASP Conf. Ser., 294, 39
Perryman, M. A. C., & ESA, eds. 1997, The HIPPARCOS and TYCHO catalogues, Astrometric and photometric star catalogues derived from the ESA HIPPARCOS Space Astrometry Mission, ESA Spec. Publ., 1200
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical recipes in C. The art of scientific computing (Cambridge: University Press), 2nd edn.
Queloz, D., Mayor, M., Udry, S., et al. 2001, The Messenger, 105, 1
Reffert, S., Quirrenbach, A., Mitchell, D. S., et al. 2006, ApJ, 652, 661
Sadakane, K., Ohnishi, T., Ohkubo, M., & Takeda, Y. 2005, PASJ, 57, 127
Santos, N. C., Israelian, G., Mayor, M., et al. 2005, A&A, 437, 1127
Sato, B., Ando, H., Kambe, E., et al. 2003, ApJ, 597, L157
Scargle, J. D. 1982, ApJ, 263, 835
Setiawan, J., Hatzes, A. P., von der Lühe, O., et al. 2003, A&A, 398, L19
Setiawan, J., Rodmann, J., da Silva, L., et al. 2005, A&A, 437, L31
Sneden, C. A. 1973, Ph.D. Thesis, AA, University of Texas at Austin
Valenti, J. A., Butler, R. P., & Marcy, G. W. 1995, PASP, 107, 966