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# Discovery of a planet around the K giant star 4 Ursae Majoris★

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**ABSTRACT**

For the past 3 years we have been monitoring a sample of 62 K giant stars using precise stellar radial velocity measurements with high accuracy taken at the Thüringer Landessternwarte Tautenburg. We search for sub-stellar companions to giant stars and try to understand the nature of the diverse radial velocity variations exhibited by K giant stars. We present precise stellar radial velocity measurements of the K1III giant star 4 UMa (HD 73108). These were obtained using the coudé echelle spectrograph of 2-m Alfred Jensch Telescope. The wavelength reference for the radial velocity measurements was provided by an iodine absorption cell. Our measurements reveal that the radial velocity of 4 UMa exhibits a periodic variation of 269.3 days with a semiamplitude $K = 216.8$ m s$^{-1}$. A Keplerian orbit with an eccentricity, $e = 0.43 \pm 0.02$ is the most reasonable explanation for the radial velocity variations. The orbit yields a mass function, $f(m) = (2.05 \pm 0.24) \times 10^{-7}\ M_{\odot}$. From our high resolution spectra we calculate a metallicity of $-0.25 \pm 0.05$ and derive a stellar mass of 1.23 $M_{\odot} \pm 0.15$ for the host star. The K giant star 4 UMa hosts a substellar companion with minimum mass $M \sin i = 7.1 \pm 1.6\ M_{\rm Jupiter}$.

**Key words.** star: general – stars: variables – stars: individual: 4 UMa – techniques: radial velocities – stars: late-type – stars: planetary systems

## 1. Introduction

More than 200 extrasolar planets around main sequence stars have been detected via radial velocity method (RV), however most of these are around stars with masses of approximately one solar mass. We thus have a very poor understanding of how the stellar mass influences planet formation, particularly for more massive stars. Although a few radial velocity searches have been undertaken for planets around low mass stars (Delfosse et al. 1999; Endl et al. 2003), there have been fewer attempts to search for planets around intermediate mass stars. The reason is that RV searches are ill-suited for early-type, more massive main sequence stars. These stars are hotter and thus have fewer spectral lines, which are broadened significantly by the high rotation rates common among early-type A-F stars.

In spite of the lower RV precision, there are on-going attempts to search for planets around intermediate mass A–F stars (Galland et al. 2005a) and these have produced two substellar companions. A 9.1 $M_{\rm Jupiter}$ mass companion was found in a 388-d orbit around the F-type star HD 33564 ($M = 1.25\ M_{\odot}$) by Galland et al. (2005b). A candidate brown dwarf (25 $M_{\rm Jupiter}$) in a 28-day orbit was found around the A9V star HD 180777 (Galland et al. 2006).

An alternative approach to search for planets around more massive stars is to look at intermediate mass stars that have evolved off the main sequence and up the giant branch. These stars are cooler and thus have a plethora of stellar lines. This along with their slower rotation rates make them amenable to high precision RV measurements. Two difficulties are encountered in this approach. First, unlike for main sequence stars, K giants of widely different masses can have similar effective temperatures. Second, giant stars show intrinsic variations due to stellar oscillations. These short period (2−10 days) variations are likely caused by radial and/or nonradial p-mode oscillations (e.g. Hatzes & Cochran 1994). These oscillations add intrinsic RV "noise" making the detection of extrasolar planets more difficult. In spite of these challenges, searching for planets around giant stars can give us information about the process of planet formation around intermediate mass stars.

The first indications of sub-stellar companions around giant stars was found by Hatzes & Cochran (1993) who discovered long period RV variations in three K giant stars. They proposed two viable hypotheses for these variations: sub-stellar companions or rotational modulation. The expected rotational periods of K giants are several hundreds of days which are comparable to the observed RV periods. If a large surface inhomogeneity (e.g. starspot) were on the surface this would create distortions of the spectral line profiles which would be detected as an RV variation with the rotation period of the star. For these reasons the nature of the long period RV variations was not clear.

Subsequent studies have established that giant stars can indeed host extrasolar planets. Frink et al. (2002) discovered the first extrasolar planet around the K giant star HD 137759 ($\iota$ Dra). This was followed by the discovery of substellar companions to the K2 III star HD 47536 (Setiawan et al. 2003a) and HD 122430 (Setiawan 2003b). In the same year Sato et al. (2003) reported a planetary companion around G9 III HD 104985. Sub-stellar companions have also been reported for HD 11977

★ Based on observations obtained at the 2-m-Alfred Jensch Telescope at the Thüringer Landessternwarte Tautenburg.

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(Setiawan et al. 2005) and HD 13189 (Hatzes et al. 2005). More recently Hatzes et al. (2006) confirmed that the initial RV variations found by Hatzes & Cochran (1993) in $\beta$ Gem were in fact due to a planetary companion. This was confirmed by Reffert et al. (2006).

For most of these discoveries the planet hypothesis for the RV variations was established due to a lack of variations in other measured quantities with the RV period. Spots or stellar pulsations are expected to also produce variations in either activity indicators (Ca II H&K), photometry, and/or spectral line shape variations with the RV period. These variations were not found in the giant stars claimed to host extrasolar planets. In the case of $\iota$ Dra the high eccentricity of the orbit established its Keplerian nature.

## 2. Observations and data analysis

4 UMa (= HD 73108 = HR 3403 = HIP 42527) belongs to a sample of K giant stars that we have observed since February 2004 at the Thuringia State Observatory (Thüringer Landessternwarte Tautenburg or TLS). Observations were made using the 2 m Alfred Jensch Telescope as part of the Tautenburg Planet Search Program (TOPS). The TOPS program uses the coudé echelle spectrograph which provides a resolving power, $R = 67\,000$ and a wavelength coverage of 4700−7400 Å. A total of 46 spectra (nightly averages) of 4 UMa were taken using the iodine cell. The total exposure time ranged between 5 and 10 min depending on the weather conditions and this resulted in a signal-to-noise ratio typically greater than 150. The strategy was to make observations for this star 1−3 times per month, weather permitting. The standard CCD data reductions (bias-subtraction, flat-fielding and spectral extraction) were performed using IRAF routines.

An iodine absorption cell placed in the optical path provided the wavelength reference for the velocity measurements. The RVs were calculated by modeling the observed spectra with a high signal-to-noise ratio template of the star taken without the iodine cell and a scan of our iodine cell taken at very high resolution with the Fourier Transform spectrometer (FTS) of the McMath-Pierce telescope at Kitt Peak. The relative velocity shift between stellar and iodine absorption lines as well as the temporal and spatial variations of the instrument profile were calculated for each observation. For more details about the spectrograph, RV program, and typical measurement precision see Hatzes et al. (2005). For the bright K giant stars in our program we typically achieve an RV accuracy of about 3−5 m s$^{-1}$. A more detailed discussion of the RV accuracy for the K giant stars will be presented in a forthcoming paper on the complete Tautenburg sample.

## 3. The properties of the star 4 UMa

4 UMa has a visual magnitude of $V = 5.79$ mag and is classified in SIMBAD as K1III star. The Hipparcos parallax is 12.92 ± 0.71 mas and this implies an absolute magnitude $M_V = 0.146 \pm 0.119$ mag. The stellar parameters of 4 UMa are summarized in Table 1. These were either obtained from the literature or derived from our analysis of the stellar spectra taken without the iodine cell. Our high-quality spectra allowed us to determine accurate Fe abundances as well as the effective temperature, $T_{\rm eff}$, the surface gravity, log $g$, and the microturbulence velocity, $\xi$. The results of this analysis for 4 UMa and the rest of the Tautenburg sample will be presented in more detail in a forthcoming paper.

**Table 1.** Stellar parameters of 4 UMa.

| Spectral type | K1III | HIPPARCOS |
|---|---|---|
| $m_V$ | 5.787 ± 0.005 | mag |
| $M_V$ | 0.146 ± 0.119 | mag |
| $B - V$ | 1.197 ± 0.005 | mag |
| Parallax | 12.92 ± 0.71 | mas |
| Distance | 62.39 ± 3.43 | pc |
| Mass[a] | 1.234 ± 0.15 | $M_\odot$ |
| $R_*^a$ | 18.11 ± 1.47 | $R_\odot$ |
| Age[a] | 4.604 ± 2.0 | Gyr |
| $T_{\rm eff}^a$ | 4415 ± 70 | K |
| [Fe/H][a] | −0.25 ± 0.04 | dex |
| log $g^a$ | 1.8 ± 0.15 | dex |
| micro turbulence[a] | 1.2 ± 0.8 | km s$^{-1}$ |

[a] Döllinger et al., in preparation.

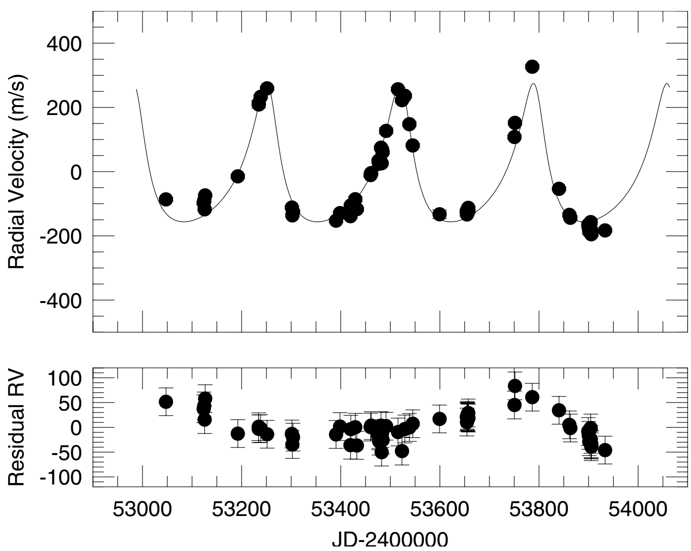


**Fig. 1.** (*Top*) radial velocity measurements for 4 UMa. The solid line is the orbital solution. (*Bottom*) residual RV variations after subtracting the contribution of the planet orbit.

The metallicity, $T_{\rm eff}$, and the absolute $V$-band magnitude as derived from Hipparcos parallaxes were used as input values to estimate the mass, age, radius, $(B - V)_0$ and, in an alternative way, the surface gravity of the program stars by comparing these to theoretical isochrones with a modified version of Jørgensen & Lindegren's (2005) method. A detailed description about the procedure is given in da Silva et al. (2006). Previous investigations have also derived stellar parameters for 4 UMa. McWilliam (1990) obtained the following values for the $T_{\rm eff}$, surface gravity log $g$ and [Fe/H]: 4370 K, 2.45 and −0.26. The corresponding values by Luck (1991) were 4400 K, 1.61 and −0.20, respectively. Both of these values are in excellent agreement with our results.

## 4. Radial velocity variations and orbital solution

The time series of our RV measurements for 4 UMa is shown in Fig. 1. There is an obvious sinusoidal variation in the RV curve with a period of approximately 270 days. This does not appear to be a pure sine wave and is thus the first hint of Keplerian motion.

An analysis using a Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) confirmed the presence of strong power at a frequency $\nu = 0.0038$ c d$^{-1}$ ($P = 271$ days). The false alarm

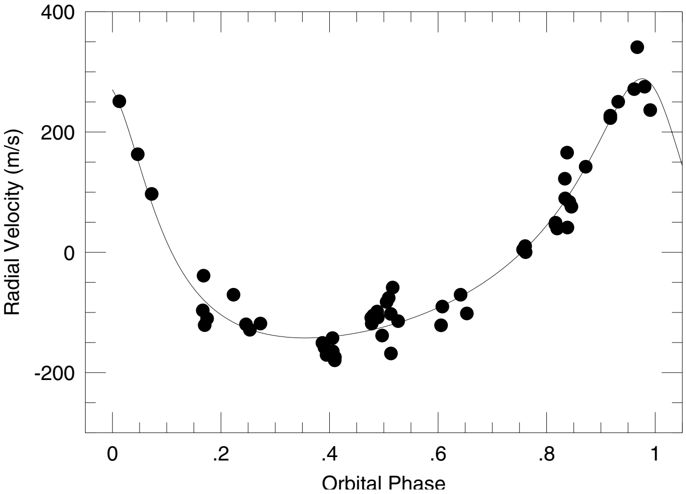


**Fig. 2.** Radial velocity measurements for 4 UMa phased to the orbital period. The line represents the orbital solution.

**Table 2.** Orbital parameters for the companion to 4 UMa.

| | |
|---|---|
| Period [days] | 269.3 ± 1.96 |
| $T_{\text{periastron}}$[JD] | 52 987.3936 ± 4.31 |
| $K$[m s$^{-1}$] | 215.55 ± 7.10 |
| $\sigma$(O–C)[m s$^{-1}$] | 28.8 |
| $e$ | 0.432 ± 0.024 |
| $\omega$[deg] | 23.81 ± 4.42 |
| $f(m)$[solar masses] | (2.045 ± 0.247) × $10^{-7}$ |
| $a$[AU] | 0.87 ± 0.04 |

probability (FAP) of this peak using the prescription in Scargle (1982) is estimated to be FAP ≈ $10^{-8}$.

An orbital solution using the RV data resulted in a period, $P$ = 269.3 ± 1.96 days and an eccentricity, $e$ = 0.43 ± 0.02. The corresponding mass function is $f(m) = (2.045 \pm 0.247) \times 10^{-7}\ M_{\odot}$. Using our derived stellar mass of $M_{\star} = 1.23\ M_{\odot} \pm 0.15$ we calculated a minimum mass for the companion of $M \sin i = 7.1 \pm 1.6\ M_{\text{Jupiter}}$. All the orbital elements are listed in Table 2. Figure 2 shows the RV variations phase-folded to the orbital period.

Although the orbital fit to the data is good, there are points that significantly from the solution. In fact, the rms scatter, $\sigma$, about the orbital solution is rather large, $\sigma \approx 30$ m s$^{-1}$, or about a factor of ten larger than our expected errors. We suspect that this results from another periodic signal in the data. The lower panel of Fig. 1 shows the residual RV variations after removal of the orbital contribution due to the planetary companion. There are clear variations with a period much larger than the orbital period. This is confirmed by the Lomb-Scargle periodogram of the radial velocity residuals shown in Fig. 3. This shows a strong peak at a frequency of $\nu = 0.00156$ c d$^{-1}$ ($P$ = 641 days). The statistical significance of this signal was estimated using a "bootstrap randomization" technique. The measured RV values were randomly shuffled keeping the observed times fixed and a periodogram for the shuffled data computed. After $2 \times 10^5$ shuffles there was no instance where the random fake data periodogram data had higher power than the data periodogram in the frequency range. This indicates that the FAP < $2 \times 10^{-6}$. This signal is thus statistically significant.

We also note that K giants show RV variations on time scales of several days and amplitudes of up to 100 m s$^{-1}$. This may also contribute to the scatter of the RV points about the orbital solution.

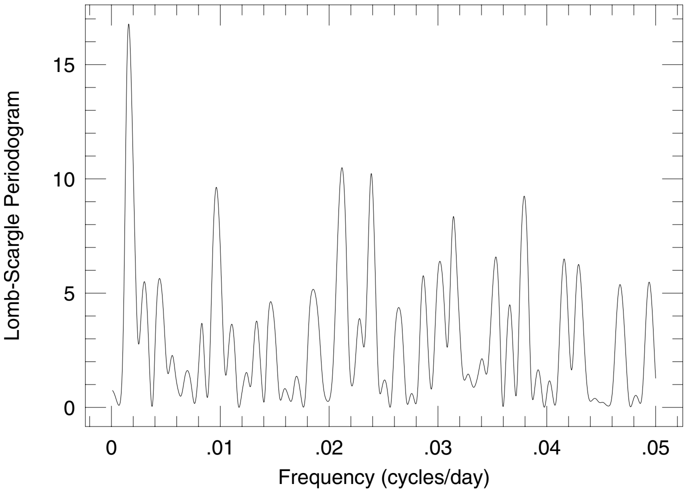


**Fig. 3.** Lomb-Scargle periodogram of the RV residuals of 4 UMa. The strong peak corresponds to a period of 641 days.

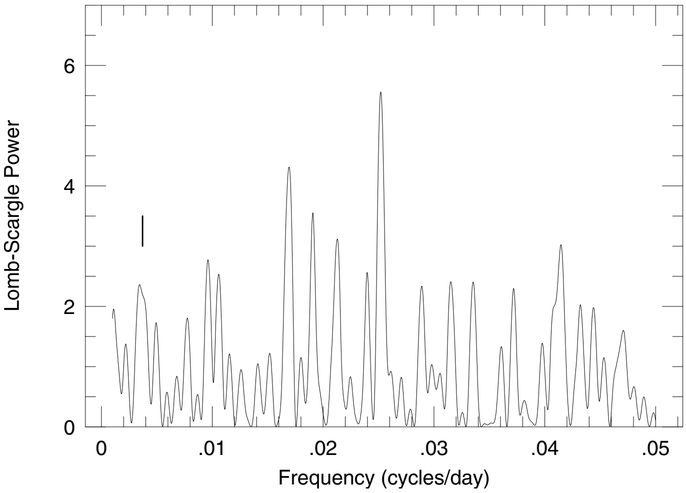


**Fig. 4.** Lomb-Scargle periodogram of the Hipparcos photometry for 4 UMa. The horizontal line marks the orbital frequency.

## 5. Hipparcos photometry

We also analyzed the Hipparcos photometry of 4 UMa in order to see if variations with the 270 day period are present. Hipparcos obtained 27 observations ("daily averages") over a 3 year period. Figure 4 shows the Lomb-Scargle periodogram of the Hipparcos photometry after averaging the multiple measurements taken within a few hours of each other. One obvious outlier that had a value more than $10\sigma$ from the mean was eliminated from the data prior to calculating the periodogram. Although there is a weak peak near the orbital frequency this is not significant and there are several peaks with more power. The highest peak is at a frequency of 0.0252 c d$^{-1}$ ($P$ = 39.698 days). Figure 5 shows the photometry phased to this period. The false alarm probability was estimated using the bootstrap randomization technique. After 100 000 such shuffles 19% of the random data periodograms showed power greater than the real periodogram. This peak is most likely not significant. It it were real it be could be due to stellar oscillations. For example, Hatzes & Cochran (1998) detected a similar period (≈50 days) in the spectral line bisector variations in Aldebaran which they attributed to oscillations.

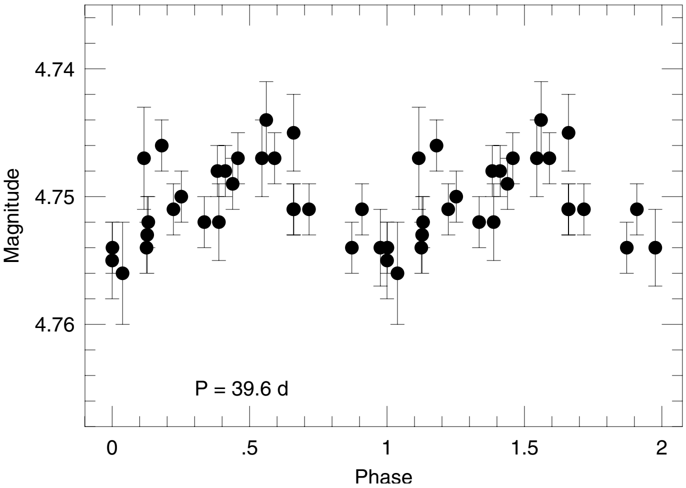


**Fig. 5.** Hipparcos photometry for 4 UMa phased to the 39.6 day photometric period.

## 6. Discussion

Our radial velocity measurements indicate that the giant star 4 UMa hosts a giant extrasolar planet. We are confident that these RV variations are due to a sub-stellar companion and not to rotational modulation for three reasons. First, the orbit is highly eccentric and such a saw-toothed RV pattern is difficult to reproduce with rotational modulation from spots or possibly even from stellar oscillations. Indeed, the high eccentricity of the companion to $\iota$ Dra was the convincing argument that this was a true companion. Second, the Hipparcos photometry does not show any significant variations at the orbital period. Finally, our periodogram analysis shows a statistically significant period at 641 days in the RV residuals for 4 UMa. We have detected two periods of several hundred days; both cannot be due to rotation. Because the RV variations of the dominant 269-d RV period is well-fit by an eccentric Keplerian orbit, we believe that this signal is due to a planetary companion. The 641-day period we have detected may indeed be due to rotational modulation, although a similar signal does not appear in the Hipparcos photometry. We caution the reader, however, that the Hipparcos photometry was not contemporaneous with our RV measurements.

At this point we do not wish to speculate as to the nature of the 641-day period that we have detected in the RV residuals. It could well be due to rotational modulation, or possibly due to a second companion. We are continuing to monitor this star and are currently making a detailed analysis of other observed quantities (H$\alpha$ for example) to see if this is the rotation period of the star.

The high eccentricity of the orbit with a value of $e = 0.43 \pm 0.02$ is not unusual for planet hosting stars, including giant stars. The companion to $\iota$ Dra has the highest eccentricity ($e = 0.7$) for a planet around a giant star. Relatively high eccentricities have also been found for the companions to HD 11977 ($e = 0.4$, Setiawan et al. 2005) and HD 13189 ($e = 0.27$, Hatzes et al. 2006). It seems that the planetary companions to giant stars can have the wide range of orbital eccentricities that are shown by planets orbiting main sequence stars.

The abundance analysis for 4 UMa shows that this star is slightly metal poor ([Fe/H] = $-0.25 \pm 0.05$). This is interesting because main sequence stars hosting exoplanets tend to to be metal rich compared to stars that do not posses exoplanets (Santos et al. 2004). Other authors (Schuler et al. 2005; da Silva et al. 2006) have also found evidence that planet hosting giant stars are metal poor. However, given the small number of planets around giant stars it is premature to conclude that these contradict the planet-metallicity trend for main sequence stars. An analysis of a larger sample of giant stars may show that those having higher metallicity indeed show a higher frequency of substellar companions.

The number of exoplanets around evolved stars is so far very limited. The discovery of the companion to 4 UMa adds to the growing list of evolved stars hosting sub-stellar companions (see Hatzes et al. 2006 and references therein). The estimated masses for the giant stars hosting planets range from 1 to 3 solar masses. In terms of the properties of planets around giant stars they have similar characteristics, masses in the range of of 2–14 $M_{\text{Jupiter}}$ and orbital periods of several hundred days (see discussion by Hatzes et al. 2006), similar to the properties of the planet around 4 UMa. These discoveries are important because they probe a stellar mass regime different from the main sequence objects that are the targets of most planet searches.

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