A Search for Exoplanets around Northern Circumpolar Stars. IV. Six Planet Candidates to the K Giants, HD 44385, HD 97619, HD 106574, HD 118904, HD 164428, and HD 202432

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Abstract

We report the discovery of long-period radial velocity (RV) variations in six intermediate-mass K-giant stars using precise RV measurements. These discoveries are part of the Search for Exoplanets around Northern Circumpolar Stars (SENS) survey being conducted at the Bohyunsan Optical Astronomy Observatory. The nature of the RV variations was investigated by looking for photometric and line shape variations. We can find no variability with the RV period in these quantities and conclude that RV variations are most likely due to unseen substellar companions. Orbital solutions for the six stars yield orbital periods in the range 418–1065 days and minimum masses in the range 1.9–8.5 M_J. These properties are typical on planets around intermediate-mass stars. Our SENS survey so far has about an 8% confirmed planet occurrence rate, and it will provide better statistics on planets around giant stars when the survey is completed.

Key words: planetary systems – stars: late-type – techniques: radial velocities

Supporting material: machine-readable table

1. Introduction

The measurement of stellar radial velocity (RV) is one of the most effective techniques employed in the search for exoplanets. At the Bohyunsan Optical Astronomical Observatory (BOAO), we have been conducting an exoplanet search program around late-type giant stars since 2004. This program has made contributions to both exoplanet and asteroseismic studies around K-giant stars (Han et al. 2008, 2010; Lee et al. 2011, 2012a, 2012b, 2014a) and exoplanet detection around G giant stars (Omiya et al. 2009, 2012; Sato et al. 2013).

In 2010, we began a new program, the Search for Exoplanet around Northern circumpolar Stars (SENS; Lee et al. 2015). The main goal of SENS is to observe stars that are accessible year-round in order to have better sampling for our targets and thus increase the planet detection efficiency. The stars of SENS were selected from the HIPPARCOS catalog with visual magnitudes of 5.0 < m_v < 7.0 and color indices of 0.6 < B−V < 1.6. The original SENS sample consist of 224 stars—5% dwarfs, 40% giant stars, and 55% unclassified stars. From the SENS survey, we detected periodic RV variations around roughly twenty G-, K-, and M-giant stars. Among them, HD 104985 (Sato et al. 2003), 11 Ursae Minoris (Döllinger et al. 2009), HD 208527 and HD 220074 (Lee et al. 2013), HD 11755, HD 12648, HD 24064 and 8 Ursae Minoris (Lee et al. 2015), HD 36384, HD 52030, and HD 208742 (Lee et al. 2017) were later shown to host planetary companions.

In this paper, the observational strategy and data reduction are summarized in Section 2. Section 3 describes the stellar properties and analysis of each host stars. In Section 4, orbital solutions are described in detail. Some possible causes of the RV variations are examined in Section 5. The discussion about the results is presented in Section 6.

2. Observation

Observations were made with the high-resolution fiber-fed Bohyunsan Observatory Echelle Spectrograph (BOES; Kim et al. 2007) of the 1.8 m telescope at BOAO. An iodine (I_2) absorption cell is equipped in BOES for precise RV measurements. BOES has three fibers with 80, 200, and 300 μm of diameter, which give resolutions of R = 90000, 45000, and 27000, respectively.

For our program, we used the 200 μm fiber. A typical exposure time of 20 minutes yielded a signal-to-noise ratio (S/N) of about 150. Since the start of the program in January 2010, we have collected 30 spectra each for HD 44385, HD 97619, HD 106574, HD 118904, HD 164428, and HD 202432. In order to check the instrumental stability, we have monitored α Ceti by standard since 2003. The long-term RV accuracy of BOES is ~7.6 m s^{-1}.

The data reduction was performed with the IRAF package for bias subtraction, flat fielding, and order extraction, etc. Once we extracted the one-dimensional spectra from the raw data, precise RVs were measured using the program RV12CELL (Han et al. 2007).

3. Stellar Characteristics

We obtained the basic stellar parameters (the visual magnitude V, parallax π, spectral type, B−V, luminosity, and RV) of the stars from Anderson & Francis (2012) based on the HIPPARCOS catalog (ESA 1997). We also adopted more
precise parallaxes from Gaia Collaboration et al. (2016). The effective temperature, log g, metallicity ([Fe/H]), and micro-turbulent velocity (\(v_{\text{micro}}\)) were estimated from TGVIT (Takeda et al. 2005). For comparison, we also obtained the effective temperature from Ammons et al. (2006) and McDonald et al. (2012, 2017). We have estimated the projected rotational velocities using a line broadening technique (Takeda et al. 2008).

The stellar radii, masses, and ages were calculated using the online tool PARAM 1.3\(^{8}\) (da Silva et al. 2006), which is based on a library of theoretical stellar isochrones (Girardi et al. 2000; Bressan et al. 2012) and Bayesian inference (Jørgensen & Lindegren 2005).

The stellar parameters of the observed stars are summarized in Table 1.

### Table 1
Stellar Parameters for the Stars

| Parameter | HD 44385 | HD 97619 | HD 106574 | HD 118904 | HD 164428 | HD 202432 |
|-----------|----------|----------|-----------|-----------|-----------|-----------|
| Spectral type | K0 | K0 | K0 III | K0 III | K5 | K2 |
| \(m_v\) (mag) | 6.771 ± 0.001 | 7.044 ± 0.001 | 5.883 ± 0.001 | 5.665 ± 0.001 | 6.388 ± 0.001 | 7.052 ± 0.001 |
| \(B-V\) (mag) | 1.266 ± 0.007 | 1.315 ± 0.008 | 1.179 ± 0.005 | 1.219 ± 0.005 | 1.452 ± 0.008 | 1.206 ± 0.009 |
| RV (km s\(^{-1}\)) | ∼14.87 ± 0.20 | ∼23.84 ± 0.17 | ∼16.48 ± 0.29 | ∼13.72 ± 0.20 | ∼8.16 ± 0.20 | ∼2.23 ± 0.20 |
| \(\pi\) (mas) | 3.92 ± 0.41 | 4.93 ± 0.42 | 7.00 ± 0.28 | 7.93 ± 0.24 | 3.82 ± 0.29 | 6.40 ± 0.40 |
| \(T_{\text{eff}}\) (K) | 4499 | 4245 | ... | 4511 | 4422 | 4569 |
| \(L_*/(L_\odot)\) | 2.6 | 2.5 | 2.2 | 2.1 | 2.0 | 1.9 |
| \(M*/(M_\odot)\) | 1.8 | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 |
| log \(g\) (cgs) | 1.80 | 1.83 | 1.78 | 1.71 | 1.62 | 1.53 |
| \(v_{\text{micro}}\) (km s\(^{-1}\)) | 2.00 ± 0.12 | 2.33 ± 0.09 | 2.18 ± 0.18 | 2.13 ± 0.10 | 1.62 ± 0.17 | 2.42 ± 0.12 |
| Age (Gyr) | 1.66 ± 0.13 | 1.54 ± 0.13 | 1.59 ± 0.06 | 1.39 ± 0.15 | 1.39 ± 0.19 | 1.32 ± 0.16 |
| \(R_*/(R_\odot)\) | 19.5 | 19.5 | 20.4 | 17.7 | 39.4 | 12.3 |
| \(\pi_{\text{rot}}\) (km s\(^{-1}\)) | 18.2 ± 1.2 | 16.7 ± 1.3 | 17.1 ± 0.9 | 14.8 ± 1.3 | 35.4 ± 2.9 | 11.1 ± 0.3 |
| \(M_*/(M_\odot)\) | 1.8 ± 0.2 | 1.3 ± 0.1 | 1.2 ± 0.1 | 1.4 ± 0.2 | 1.5 ± 0.2 | 1.2 ± 0.2 |
| \(L_*/(L_\odot)\) | 232.3 | 228.1 | 152.2 | 152.4 | 24.63 | 63.9 |
| \(v_{\text{rot}}\) (km s\(^{-1}\)) | 132.6 ± 11.1 | 109.8 ± 10.1 | 142.5 ± 9.8 | 105.6 ± 10.7 | 397.9 ± 37.8 | 54.0 ± 3.6 |
| \(v_{\text{LOS}}\) (km s\(^{-1}\)) | 2.6 ± 0.5 | 1.9 ± 0.5 | 1.7 ± 0.5 | 1.2 ± 0.5 | 2.8 ± 0.5 | 2.1 ± 0.5 |
| \(P_{\text{orb}}\) (days) | 354.1 ± 72.0 | 444.7 ± 122.0 | 508.9 ± 152.1 | 624.0 ± 265.7 | 629.6 ± 125.7 | 267.4 ± 64.1 |

### Table 2
Preliminary Orbital Solutions

| Parameter | HD 44385 b | HD 97619 b | HD 106574 b | HD 118904 b | HD 164428 b | HD 202432 b |
|-----------|-----------|-----------|-------------|-------------|-------------|-----------|
| \(P\) (days) | 473.5 ± 4.9 | 665.9 ± 9.5 | 1065.7 ± 14.6 | 676.7 ± 19.1 | 599.6 ± 8.7 | 418.8 ± 2.9 |
| \(K\) (ms\(^{-1}\)) | 104 ± 10 | 68 ± 6 | 149 ± 8 | 61 ± 8 | 109 ± 15 | 43 ± 3 |
| \(T_{\text{periastron}}\) (JD) | 2455121 ± 37 | 245238 ± 55 | 245585 ± 360 | 245478 ± 82 | 245068 ± 46 | 245908 ± 26 |
| \(e\) | 0.20 ± 0.20 | 0.23 ± 0.17 | 0.03 ± 0.03 | 0.31 ± 0.30 | 0.29 ± 0.22 | 0.21 ± 0.16 |
| \(\omega\) (degree) | 292.18 ± 28.11 | 293.53 ± 23.97 | 44.66 ± 122.15 | 29.16 ± 31.02 | 203.11 ± 26.59 | 61.24 ± 21.76 |
| \(m\) (M\(_\odot\)) | 5.9 ± 1.1 | 3.5 ± 1.3 | 8.5 ± 1.1 | 3.1 ± 1.2 | 5.7 ± 1.3 | 1.9 ± 0.4 |
| \(a\) (au) | 1.4 ± 0.1 | 1.6 ± 0.1 | 2.2 ± 0.1 | 1.7 ± 0.1 | 1.6 ± 0.1 | 1.2 ± 0.1 |
| Slope (m s\(^{-1}\) yr\(^{-1}\)) | −6.9 | 11.5 | 2.4 | 1.0 | 1.2 | 4.4 |
| \(N_{\text{disc}}\) | 35 | 35 | 31 | 38 | 30 | 29 |
| \(v_{\text{rms}}\) (ms\(^{-1}\)) | 41.5 | 26.2 | 44.0 | 33.2 | 51.6 | 12.4 |

### 4. Orbital Solutions

Here, we present the derived orbital parameters assuming that periodic RV variations are caused by Keplerian motion. An initial value of the period was determined using the Lomb-Scargle periodogram (L–S) analysis, which is appropriate for uneven sampled data and also gives an estimate of the false alarm probability (FAP) of the signal (Lomb 1976; Scargle 1982). Using this initial period, we estimated all of the orbital elements by an iterated nonlinear least-squares method. If a linear RV trend is shown, a slope is taken as an unknown parameter. Table 2 lists the orbital parameters for all stars.

#### 4.1. HD 44385

The RV data of HD 44385 are listed in Table 3 and the Keplerian motion are plotted in Figure 1. The RVs cover more than five cycles and show a slight linear trend of −6.9 ms\(^{-1}\) yr\(^{-1}\); such a linear trend is also seen in the other five

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\(^{8}\) http://stev.oapd.inaf.it/cgi-bin/param_1.3/
systems of this study. These linear RV variations may be caused by an unseen distant companion or due to some long-term and unknown intrinsic stellar variations. The orbit has a period, $P = 473.5 \pm 4.9$ days, an eccentricity, $e = 0.20 \pm 0.20$, and a semi-amplitude $K = 104 \pm 10$ m s$^{-1}$.

The RV residuals have an rms of 41.5 m s$^{-1}$, which is larger than the typical intrinsic RV variations of K-giant stars. The scaling relationship of Kjeldsen & Bedding (1995) yields an amplitude of 15 m s$^{-1}$ for stellar oscillations, which may contribute to rms of the RV residuals. However, the excess residual RV scatter is still too large. We discuss this large residual RV scatter in Section 6.

4.2. HD 97619

The RV data of HD 97619 and the Keplerian orbit are plotted in Figure 2. The RVs cover more than three cycles, and these also show a slight linear trend of 11.5 m s$^{-1}$ yr$^{-1}$, again possibly due a third body in the system. The best Keplerian fit yields the orbital elements of $P = 665.9 \pm 9.5$ days, $e = 0.23 \pm 0.17$, and $K = 68 \pm 6$ m s$^{-1}$. The host star has a mass just a little higher than the Sun, as does the other host star HD 202432. It hosts a planet candidate with the lowest mass among the companions in the present study. The residuals have an rms of 26.2 m s$^{-1}$, consistent with the expected RV scatter (so called “jitter”).

4.3. HD 106574

The RV data of HD 106574 and the best Keplerian orbital fit are plotted in Figure 3. The RVs cover about two cycles. The orbit has a period of 1065.7 $\pm$ 14.6 days, an eccentricity of 0.03 $\pm$ 0.03, and a semi-amplitude of 149 $\pm$ 8 m s$^{-1}$. Unlike the other five systems, this system has a nearly circular orbit. The planet candidate is the most massive among our six stars. The residuals have an rms of 44.0 m s$^{-1}$. This is considerably

| JD     | $\Delta$RV (m s$^{-1}$) | $\pm \sigma$ (m s$^{-1}$) | JD     | $\Delta$RV (m s$^{-1}$) | $\pm \sigma$ (m s$^{-1}$) |
|--------|------------------------|---------------------------|--------|------------------------|---------------------------|
| 5249.186772 | -4.5 13.2 | 6739.992829 | 56.6 10.9 |
| 5277.062617 | -7.0 14.9 | 6922.262909 | -95.2 11.2 |
| 5554.20620 | 22.8 13.3 | 6965.959830 | -56.6 10.9 |
| 5843.317817 | -10.6 11.1 | 7066.218427 | 77.5 13.1 |
| 5934.119026 | -40.3 10.2 | 7094.061052 | 75.4 16.3 |
| 5963.063139 | -80.1 11.0 | 7171.018942 | 49.5 18.4 |
| 6024.980916 | -87.6 11.6 | 7301.155470 | -96.0 11.6 |
| 6074.04223 | -20.4 16.3 | 7330.319704 | -124.3 12.7 |
| 6210.34239 | 72.6 13.3 | 7378.167893 | -112.0 9.7 |
| 6258.199914 | 27.7 10.7 | 7491.026213 | 41.8 13.7 |
| 6261.229862 | 31.9 10.3 | 7526.987711 | 78.5 11.9 |
| 6287.184819 | 11.3 21.1 | 7529.996251 | 82.5 11.4 |
| 6346.09790 | -62.6 10.9 | 7704.047239 | 45.0 10.6 |
| 6551.34705 | 111.9 13.9 | 7757.136001 | -159.7 10.5 |
| 6582.21632 | 104.7 15.4 | 7758.104706 | -165.1 10.9 |
| 6582.294436 | 96.6 10.8 | 7856.004581 | -111.0 9.8 |
| 6583.251127 | 132.0 12.6 | 8151.089358 | -24.9 15.7 |
| 6617.049357 | 137.9 10.8 |
larger than the value of 21 m s\(^{-1}\) predicted by the Kjeldsen & Bedding (1995) relationship. This possibly indicates an additional source of stellar variability as HD 44385.

4.4. HD 118904

The RV data of HD 118904 and the best Keplerian orbital fit are plotted in Figure 4. The RVs cover more than three cycles. The orbital fit yields a period of 676.7 ± 19.1 days, an eccentricity of 0.31 ± 0.30, and a semi-amplitude of 61 ± 8 m s\(^{-1}\). The rms RV residuals have a value of 33.2 m s\(^{-1}\), also the normal case for a K-giant star.

4.5. HD 164428

The RV data of HD 164428 and the Keplerian orbital fit are plotted in Figure 5. The RVs cover more than four cycles. The orbit has a period of 599.6 ± 8.7 days, an eccentricity of 0.29 ± 0.22, and a semi-amplitude of 109 ± 15 m s\(^{-1}\). The planet candidate has a similar mass as HD 44385 b. The rms scatter about the orbit is 51.6 m s\(^{-1}\), which is the largest jitter seen in our six systems, and is consistent with the predicted value of \(~50\) m s\(^{-1}\) for the stellar oscillations according to scaling relationships.

4.6. HD 202432

The RV data of HD 202432 and the best Keplerian orbital fit are plotted in Figure 6. The RVs cover six cycles and show a slight linear trend of 4.4 m s\(^{-1}\) yr\(^{-1}\). The Keplerian fit yields a period of 418.8 ± 2.9 days, an eccentricity of 0.21 ± 0.16, and a semi-amplitude of 43 ± 3 m s\(^{-1}\). An rms of RV residuals is 12.4 m s\(^{-1}\), a value consistent with the expected velocity amplitude of 10 m s\(^{-1}\) for stellar oscillations.

5. The Cause of the RV Variations

The periodic variations of RVs may be also intrinsic to the star such as rotational modulation or stellar pulsations by surface features. To identify the nature of the RV variations, we investigated Ca\(\text{II}\) H lines, photometric data, and spectral line profile variations.

5.1. Surface Activity

A rotating star with surface features such as spots or plage caused by magnetic activity will exhibit periodic RV variations, which can be misinterpreted as a planetary signal (Queloz et al. 2001). The Ca\(\text{II}\) H line (3968.5 Å) has often been used as a good indicator of stellar activity (Eberhard & Schwarzschild 1913). If there is chromospheric activity, an emission line may appear at the center of the Ca\(\text{II}\) H absorption line profile on the core of the line, which may be partially filled in.
The Ca II H lines of each host star are shown in Figure 8. There appears to be no noteworthy emission in the core of the Ca II H line for any target stars.

5.2. Photometric Variations

To check for any photometric variations of the stars, we used HIPPARCOS archival data. HIPPARCOS data cover the period between 1989 November and 1993 March. Although the measurements are not contemporaneous with our observations, it is still useful to check whether the HIPPARCOS data show any periodic photometric variability. The HIPPARCOS catalog provides a total of 160, 148, 143, 119, 122, and 114 observations of the HD 44385, HD 97619, HD 106574, HD 118904, HD 164428, and HD 202432, respectively.

The rms scatter of the data is 0.011, 0.011, 0.007, 0.011, 0.009, and 0.010 mag for each star, respectively. Their scatter is comparable to the photometric uncertainties of HIPPARCOS data, which ranges from 0.007 to 0.011 mag. We do not see any significant photometric variability of the stars. We also checked periodicity of HIPPARCOS data from the L–S periodogram, and could not find any significant periodicity corresponding to that of the RV variations (middle panels in the Figures 9–14).

5.3. Line Bisector Variations

The examination of spectral line shape is an important tool to help identify other origins of RV variations than Keplerian motion (Hatzes & Cochran 1998). Orbital motion by a companion should cause a Doppler shift without a change of the line shape, whereas RV variations caused by rotational modulation from stellar surface structure should be accompanied by line shape variations. We thus investigated the change of the spectral line shapes using two indicators: the bisector velocity curvature and the bisector velocity span (BVS).

To measure the line bisectors, we selected the lines Ca I 6122.2, 6439.1, 6462.6, 6717.7; Cr I 6330.1; Fe I 6141.7, 6393.6, 6411.7, 6677.9, 6750.2; Fe II 6151.6; Ni I 6643.6, 6767.8; Ti I 6085.2, 6742.6; V I 6039.7, 6081.4. These lines are free from I2 and telluric absorption lines and are relatively deep. The L–S periodogram of bisectors does not show any significant periodicity associated with those of RV variations (bottom panels in Figures 9–14).

6. Discussion

We have found long-period RV variations of six K-giant stars. The stars show no variations in the line shapes as measured by the spectral line bisectors. HD 44385 does show a weak signal in the bisector curvature measurements (BVS), but this does not seem to be significant (FAP $\leq 0.1$). We note that a lack of bisector measurements is not proof of the planetary nature. High-quality bisector measurements are difficult to make as these require high spectral resolution and high S/N data. In general, these are of much lower quality than the RV measurements. If we found bisector variations with the RV period, then the planet hypothesis is refuted. On the other hand, a lack of bisector variations is not sufficient proof of the existence of the planet. It could well be that a phenomenon produces measurable RV variations but small bisector variations that are difficult to measure.

The stars also seem to show a lack of variations in the HIPPARCOS photometry. Only one star, HD 106574, shows a weak peak in the L–S periodogram at the RV period. Again, this peak seems to be of low significance. However, the lack of photometric variations is merely suggestive, as the HIPPARCOS measurements were not contemporaneous to our data.

HD 44385, HD 106574, and HD 118904 have larger RV scatters than those predicted by the Kjeldsen & Bedding (1995) relationship. Later spectral type stars, such as HD 106574 and HD 118904, show larger RV scatters than those given in Sato.
et al. (2005), Hekker et al. (2006). Lee et al. (2012b) also have detected an exoplanet with similar orbital parameters and rms of the RV residuals. Other exoplanets discovered using BOES have shown large RV scatters (Lee et al. 2013, 2014a, 2014b, 2015; Hatzes et al. 2015, 2018).

RV scatter in giant stars may have its origin not only from the stellar pulsations but also from the stellar activities. Hatzes & Cochran (1993) found RV variations in $\alpha$ Boo with a period of 233 days and an amplitude of $\sim 200$ m s$^{-1}$. This RV period was the same period found in the He I 10830 variations in this star by Lambert (1987). He I 10830 is a chromospheric activity indicator. In this case, large RV variations are clearly due to the stellar activity.

Activity in giant stars is poorly understood and it may be that these are often not accompanied by variations in the “classic” indicators of stellar activity. We do not know the timescales or RV amplitudes of such activity jitter for these stars, which may have contributed to the RV scatters seen in some of our stars. The exact cause of large RV scatters seen in our stars is yet to be understood by further study.

Figure 8. Spectra in the region of the Ca II H line. The vertical dotted-line is located in the core of the Ca II H profiles (3968.5 Å).

Figure 9. Top to bottom: L–S periodogram of the RV measurements, residual RVs, HIPPARCOS photometry, and the line bisectors of the span and curvature for HD 44385. The vertical dashed line represents a 473-day period.

Figure 10. Top to bottom: L–S periodogram of the RV measurements, residual RVs, HIPPARCOS photometry, and the line bisectors of the span and curvature for HD 97619. The vertical dashed line represents a 667-day period.
Rotating stars with surface features can also exhibit periodic RV variations, which can be mimic a “planetary like” signal. Our stars appear to be relatively inactive as shown by an absence of emission in the core of CaII K lines. Another check on rotational modulation can come from estimates of the rotational period of the star.

From $v_{\text{rot}} \sin i$ and $R_*$ (Table 1), we estimate upper limits on the rotational period of $354.1 \pm 72.0$ days for HD 44385, $444.7 \pm 122.0$ days for HD 97619, $508.9 \pm 152.1$ days for HD 106574, $624.0 \pm 265.7$ days for HD 118904, $629.6 \pm 125.7$ days for HD 164428, and $267.4 \pm 64.1$ days for HD 202432. HD 118904 and HD 164428 have estimated rotation periods comparable to the RV periods. For HD 44385, HD 97619, HD 106574, and HD 202432, the maximum rotational periods are significantly larger than the RV periods. For these four stars, our estimated rotational periods further support that we are not seeing rotational modulation.

Another explanation for the RV variations in the six stars is a new, unknown form of stellar oscillation. One possibility is oscillatory convective modes. These have been proposed to explain the long-period variables (Saio et al. 2015), stars that are more evolved than the K-giant stars of our work. Coincidentally, only one of stars, HD 164428, is rather evolved with stellar radius larger than $20 R_\odot$. However, given that we know so little about long-period oscillations in K-giant stars, it seems that at the present time, the most likely explanation for the RV variations in our stars is Keplerian motion by planetary companions.

All of our targets are evolved intermediate-mass stars. If the variations are due to planetary companions, our detections add to the sample of exoplanets around stars more massive than the Sun. Two of our stars have masses $\geq 1.5 M_\odot$. Of the approximately 2200 exoplanets with good orbits and planet mass determinations, less than 5% of the host stars have masses greater than $1.5 M_\odot$ (source: exoplanets.org). Exoplanets around host stars with $M \geq 2 M_\odot$ have a median $m \sin i$ of 2.7 $M_J$ and a median orbital period of $\sim 400$ days. Thus, the companions to our six K giants have properties that are typical for planets around massive stars: massive giant planets ($1.9-8.5 M_J$) with orbital periods of several hundreds of days.

Although the SENS survey is not yet complete, at this stage we can still make a rough estimate of the planet frequency of our sample. We have found periodic variations in 31 of our sample of 224 stars. Among these, 17 stars have confirmed planets, which is a planet occurrence rate of about 8%. If all of the RV variations are planetary in nature, then the occurrence rate can be as high as $\sim 10%$. This is largely in line with the expectation that $\sim 10%$ giant stars have planetary companions (Mulders et al. 2015). A more detailed analysis of the statistics can be made once the SENS survey is completed.

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References

Ammons, S. M., Robinson, S. E., Strader, J., et al. 2006, ApJ, 638, 1004
Anderson, E., & Francis, C. 2012, ApJ, 38, 331
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
da Silva, L., Girardi, L., Pasquini, L., et al. 2006, A&A, 458, 609
Döllinger, M. P., Hatzes, A. P., Pasquini, L., Guenther, E. W., & Hartmann, M. 2009, A&A, 505, 1311
Eberhard, G., & Schwarzschild, K. 1913, ApJ, 38, 292
ESA 1997, yCat, 1239, 0
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Han, I., Kim, K.-M., Byeong-Cheol, L., & Valyavin, G. 2007, PASP, 119, 1052
Han, I., Lee, B.-C., Kim, K.-M., et al. 2010, A&A, 509, A24
Han, I., Lee, B.-C., Kim, K.-M., & Mkrtichian, D. E. 2008, JKAS, 41, 59
Hatzes, A. P., & Cochran, W. D. 1993, ApJ, 413, 339
Hatzes, A. P., & Cochran, W. D. 1998, in ASP Conf. Ser. 154, Cool Stars, Stellar Systems, and the Sun, ed. R. A. Donahue & J. A. Bookbinder (San Francisco, CA: ASP), 311
Hatzes, A. P., Cochran, W. D., Endl, M., et al. 2015, A&A, 580, A31
Hatzes, A. P., Endl, M., Cochran, W. D., et al. 2018, AJ, 155, 120
Hekker, S., Reffert, S., Quirrenbach, A., et al. 2006, A&A, 454, 943
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Jørgensen, B. R., & Lindegren, L. 2005, A&A, 436, 127
Kim, K.-M., Han, I., Valyavin, G. G., et al. 2007, PASP, 119, 1052
Kjeldsen, H., & Bedding, T. R. 1995, A&A, 293, 87
Lambert, D. L. 1987, ApJS, 65, 255
Lee, B.-C., Han, I., & Park, M.-G. 2013, A&A, 549, A2
Lee, B.-C., Han, I., Park, M.-G., et al. 2014a, A&A, 566, A67
Lee, B.-C., Han, I., Park, M.-G., et al. 2014b, JKAS, 47, 69
Lee, B.-C., Han, I., Park, M.-G., Mkrtichian, D. E., & Kim, K.-M. 2012a, A&A, 546, A5
Lee, B.-C., Jeong, G., Park, M.-G., et al. 2017, ApJ, 844, 36
Lee, B.-C., Mkrtichian, D. E., Han, I., Kim, K.-M., & Park, M.-G. 2011, A&A, 529, A134
Lee, B.-C., Mkrtichian, D. E., Han, I., Park, M.-G., & Kim, K.-M. 2012b, A&A, 548, A118
Lee, B.-C., Park, M.-G., Lee, S.-M., et al. 2015, A&A, 584, A79
Lomb, N. R. 1976, Ap&SS, 39, 447
McDonald, I., Zijlstra, A. A., & Boyer, M. L. 2012, MNRAS, 427, 343
McDonald, I., Zijlstra, A. A., & Watson, R. A. 2017, MNRAS, 471, 770
Mulders, G. D., Pascucci, I., & Apai, D. 2015, ApJ, 798, 112
Omiya, M., Han, I., Izumiura, H., et al. 2012, PASJ, 64, 34
Omiya, M., Izumiura, H., Han, I., et al. 2009, PASJ, 61, 825
Queloz, D., Henry, G. W., Sivan, J. P., et al. 2001, A&A, 379, 279
Sato, B., Wood, P. R., Takayama, M., & Ita, Y. 2015, MNRAS, 452, 3863
Sato, B., Ando, H., Kambe, E., et al. 2003, ApJL, 597, L157
Sato, B., Kambe, E., Takeda, Y., et al. 2005, PASJ, 57, 97
Sato, B., Omiya, M., Harakawa, H., et al. 2013, PASJ, 65, 85
Scargle, J. D. 1982, ApJ, 263, 835
Takeda, Y., Ohtoku, M., Sato, B., Kambe, E., & Sadakane, K. 2005, PASJ, 57, 27
Takeda, Y., Sato, B., & Murata, D. 2008, PASJ, 60, 781

Figure 13. Top to bottom: L–S periodogram of the RV measurements, residual RVs, HIPPARCOS photometry, and the line bisectors of the span and curvature for HD 164428. The vertical dashed line represents a 594-day period.

Figure 14. Top to bottom: L–S periodogram of the RV measurements, residual RVs, HIPPARCOS photometry, and the line bisectors of the span and curvature for HD 202432. The vertical dashed line represents a 422-day period.