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CONFIRMATION OF THE EXOPLANET AROUND β GEM FROM THE RV OBSERVATIONS USING BOES

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ABSTRACT

To detect exoplanets and study pulsation of K giant stars, we have observed precise RV (radial velocity) of about 55 early K giant (K0 - K4) stars brighter than V = 5 magnitude since 2003 by using BOES, a high resolution Echelle spectrograph attached to the 1.8 m telescope at BOAO (Bohyunsan Optical Astronomy Observatory). We detected periodic RV variation of K0 III star β Gem (HD 62509) with a period P = 596.6 $\pm$ 2.3 days and a semi-amplitude K = 44.8 $\pm$ 0.7 $\mathrm{m\,s^{-1}}$. If we adopt 1.7 $M_{\odot}$ for the mass of β Gem , this yields the minimum mass of the companion $m \sin i = 2.64\,M_{Jupiter}$. Our results agree well with Hatzes et al. (2006) and Reffert et al. (2006), and confirm their discovery of a planetary object around β Gem . We also confirmed about 192 minutes short period stellar oscillation found by Hatzes and Zechmeister (2007). This is the first report of exoplanet detection using BOES and demonstrates that the RV observation using BOES is accurate and stable enough to detect exoplanets around bright K giant stars.

Key words : exoplanet — K-giants — β Gem — radial velocity

I. INTRODUCTION

Since the first exoplanet was discovered in 1995, more than 200 exoplanets have been detected. Up to now, majority of exoplanets were detected by radial velocity measurements around low mass F-G dwarf stars. Existence of planets around intermediate mass early-type stars and their planetary parameters have not been investigated well due to their fast rotational velocities and lack of appropriate number of sharp absorption lines in their spectra. When intermediate mass stars evolve toward the red giant stage, they go through G and K-giant phase, where many sharp absorption lines appropriate for high precision RV measurements are available. Therefore K and G-giant stars are promising targets for detecting exoplanets with RV technique. There are several on-going exoplanet surveys for K and G giant stars and about 7 exoplanets were detected (Hatzes et al. 2006) and (Sato et al. 2007).

We have conducted a precise RV observations using the 1.8m telescope at BOAO (Bohyunsan Optical Astronomy Observatory) since 2003 to search for exoplanets around K giant stars and to study their pulsations and surface magnetic and spot activity. Our sample consists of about 55 early K (K0 - K4) giant stars and additional 10 M-giants, several Ap stars and F-type yellow super-giants. Most of them are brighter than fifth magnitude. In this paper we present the result of the RV observations conducted on β Gem .

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II. THE TARGET STAR

β Gem (HIP 37826, HD 6509, HR 2990, Pollux) is one of the brightest nearby giant stars (V=1.16, $B-V$ = 0.99, KOIII) in the sky. Some stellar parameters of β Gem are listed in Table 1. We estimated the atmospheric parameters of β Gem from the spectra obtained by using BOES and the analysis done by using the TGVIT program by Takeda et al. (2002). Table 2. shows the estimated atmospheric parameters with some results determined by other authors. We see that our estimation is close to the mean value of other determinations.

The RV variation of β Gem has been known since 1980s. Walker et al. (1989) first detected β Gem's RV variation of about 30 $\mathrm{m\,s^{-1}}$. Two different values of the RV variation of P = 585 days and 558 days were reported by Larson et al. (1993) and Hatzes & Cochran (1993) respectively. Though the reality of the RV variation was certain, they could not identify the cause of the RV variation. They mentioned several possibilities such as the low mass companion, rotational modulation of surface features, and stellar pulsation. After more than 10 years' observation, Hatzes et al. (2006) and Reffert et al. (2006) concluded that the period of the RV variation is about 590 days and the cause of the RV variation is due to a planet with minimum mass of

TABLE 1.
SOME STELLAR PARAMETERS OF β GEM

PARAMETER	VALUE	REFERENCE
m_V	1.16	HIPPARCOS
$B-V$	0.99	HIPPARCOS
PARALLAX (MAS)	96.74 ± 0.87	HIPPARCOS
DIAMETER (MAS)	7.98 ± 0.08	NORDGREN (2001)

TABLE 2.
ATMOSPHERIC PARAMETERS OF β GEM

$T_{\rm eff}$	$log\,g$	[Fe/H]	reference
4850	2.96	−0.07	McWilliam (1990)
4850	2.52	0.08	Gray et al. (2003)
4666	2.69	0.19	Allende-Prieto et al. (2004)
4858±20	2.78±0.065	0.19	this study

about $2.5 M_{Jupiter}$.

III. OBSERVATIONS AND DATA REDUCTION

Observations of β Gem were carried out during Apr. 2003 - Feb. 2008 using the fiber-fed high resolution Echelle spectrograph (BOES) attached to the 1.8 m telescope at BOAO. BOES has three fibers with diameter of 80, 200, and 300 μm. The measured resolving power for each fiber is R = 90000, 45000, and 30000 respectively. The efficiency is as high as 15 %. Using a 2k×4k CCD, the wavelength coverage of BOES is 3600 – 10500 Å with 86 spectral orders in a single exposure. BOES is also equipped with an iodine gas absorption cell for precise radial velocity measurements. A more detailed information of BOES can be found in Kim et al. (2007).

All the observations of β Gem were conducted using 80 μm fiber to achieve the highest resolving power and RV accuracy. A typical exposure time was 200 s achieving a S/N ratio of 150. For the precise relative wavelength calibration and the modeling of instrument profile, all spectra were obtained through the iodine absorption cell.

The extraction of normalized 1D spectra was done by using the IRAF package following standard procedures (bias subtraction, background removal, flat fielding, and wavelength calibration). Then radial velocities were measured by using the RVI2CELL code developed Han et al. (2007). This code adopted basically the same algorithm and procedure described by Butler et al. (1996). However we model the instrument profile using the least squares method descried in Endl et al. (2000). We solved the matrix equation by using a singular value decomposition method instead of the maximum entropy method adopted by Endl et al. (2000).

TABLE 4.
ORBITAL PARAMETERS OF β GEM

Period (days)	596.6 ± 2.26
K ($\rm ms^{-1}$)	44.8 ± 0.7
e	0.011 ± 0.033
$T_{periastron}$	2450969.8 ± 98.8
ω (deg)	167.7 ± 13
m sin i ($M_{Jupiter}$)	2.64 ± 0.2
a (A.U.)	1.66 ± 0.13
rms ($\rm ms^{-1}$)	9.1

Table 3 and Figure 1 show the observed radial velocities. The observed data cover about 4.5 years and the typical accuracy is about 6 $\rm m\,s^{-1}$.

IV. ORBITAL PARAMETERS AND COMPANION MASS

Orbital parameters were estimated by using the nonlinear least squares method. Table 4 lists the estimated orbital parameters and the orbit is shown by the solid line in Fig. 1. The estimated orbital parameters agree very well with the results of Hatzes et al. (2006) and Reffert et al. (2006). By investigating line profile variation and Hipparcos photometry, they argued that the RV variation is due to orbital motion by an unseen low mass companion. To determine the mass of the companion, we first estimate the mass of the host star. Allende Prieto & Lambert (1999), and Drake & Smith (1991) estimated the mass of β Gem as $M = 1.7\,M_\odot$. We estimated the mass of β Gem by using the stellar parameters in Tables 1 and 2 - parallax, angular diameter, and log g. Our estimation is $1.73\,M_\odot$, which

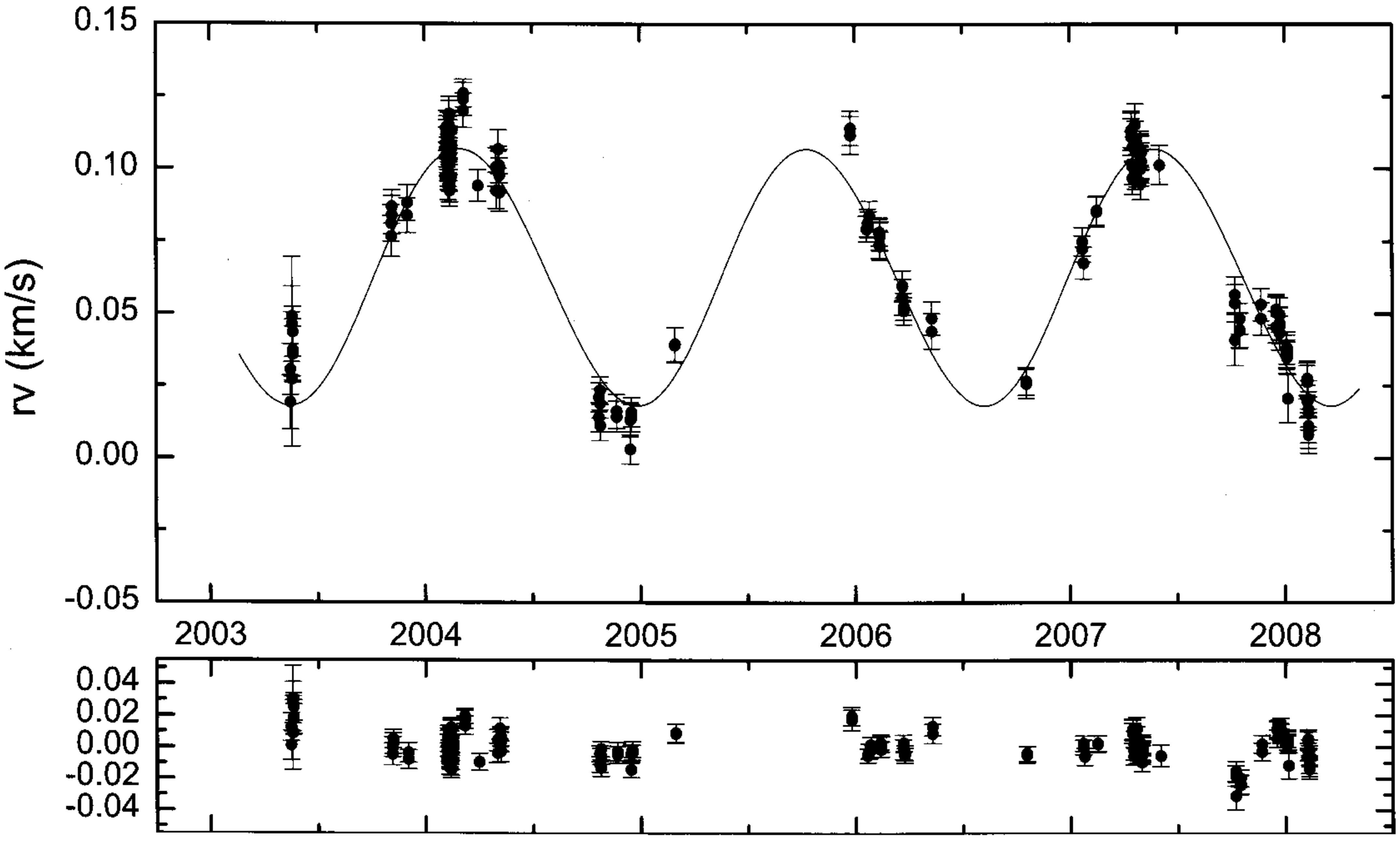

Fig. 1.— Top panel: relative RV of β Gem with he best-fit orbit. Bottom panel: plot of the residuals after subtracting the orbit. The r.m.s. residual is 9.1 ms^{-1}.

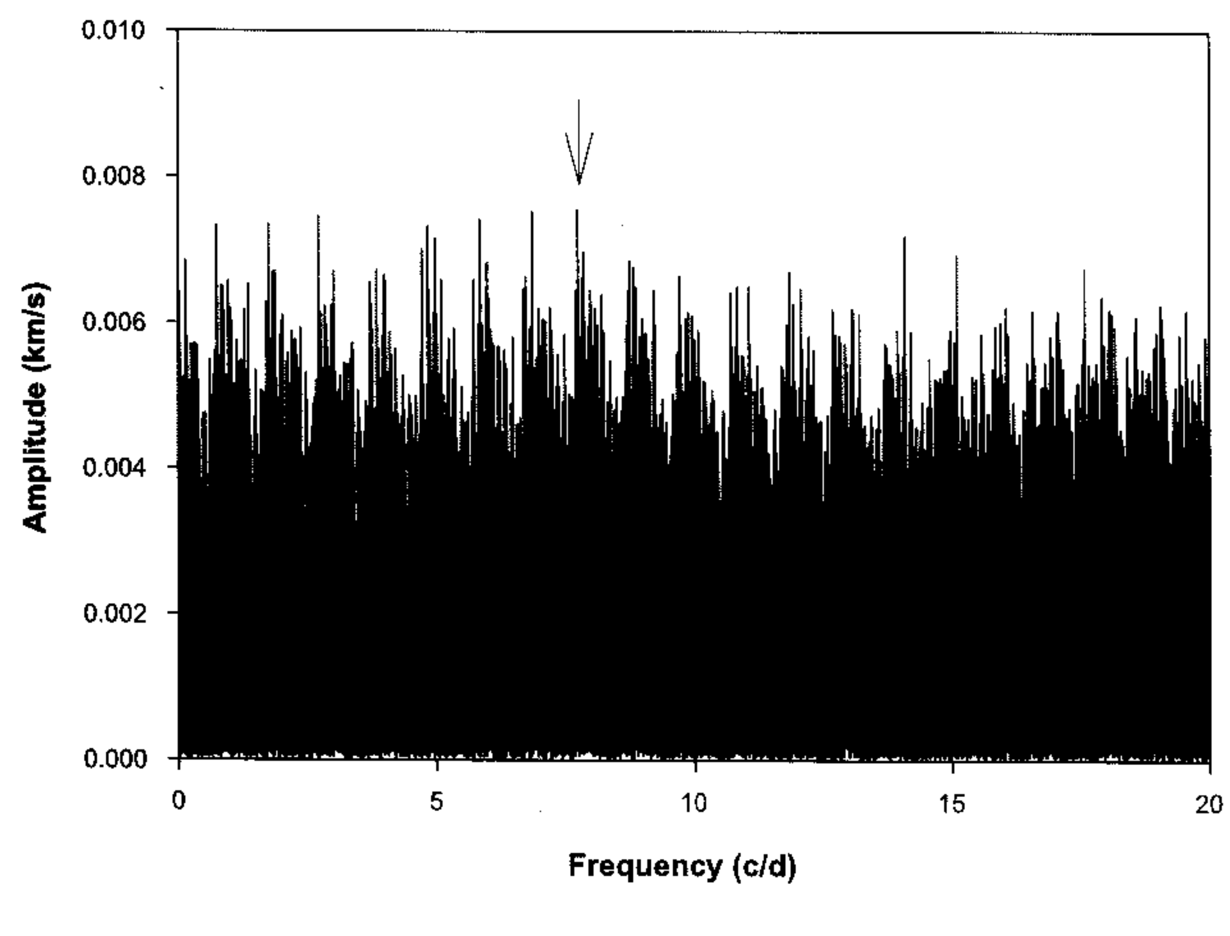

Fig. 2.— The amplitude DFT spectrum of residual data. Arrow indicated the largest peak at periodogram at 7.487 c/d that is surrounded by alias and noise peaks.

agrees well with the result of Allande Prieto & Lambert (1999). It may again indicate the reliability of our estimation of the atmospheric parameters. Adopting $M = 1.7\,M_{\odot}$, we estimate the mass of the companion as $m \sin i = 2.47\,M_{Jupiter}$.

The r.m.s. residual after subtracting the orbit from the observed data is 9.1 $\mathrm{m\,s}^{-1}$. This is a little bit larger than the estimated error. It may be due to an additional companion, or the small intrinsic RV variability of β Gem . We searched for possible periodic signal in the residual. Fig. 2 shows the periodogram of the residual. We find the largest peak at frequency 7.487 c/d (86.7 μHz). Though this is not significant statistically, it is close to the frequency 86.91 μHz discovered recently in β Gem by Hatzes & Zechmeister (2007).

β Gem does not show large intrinsic RV variation. It is rather unusual for K giant stars. More than 70 % of our 55 K giants show intrinsic RV variation larger than several tens of $\mathrm{m\,s}^{-1}$. These variations are mostly due to stellar rotation, surface spots, pulsation, or binarity.

V. SUMMARY AND CONCLUSION

From the RV data of β Gem obtained during 2003 - 2008 by using BOES, we determined the period and orbital parameters. Our determinations agree well with the results of Hatzes et al. (2006) and Reffert et al. (2006), and confirm their detection of an exoplanet with a minimum mass $m \sin i = 2.64\,M_{Jupiter}$. Though the cause of the 44.8 ms^{-1} RV variation is almost certainly due to orbital motion, it is nevertheless still important to continue RV observations to improve the orbital parameters and to look for additional planets or intrinsic variations. Our observation adds about two more years of data to other groups with equivalent accuracy. This is the first report of exoplanet detection using BOES. The result of this study demonstrates that RV observation with BOES is accurate and stable enough to detect exoplanets around bright K giant stars.

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TABLE 3.
RELATIVE RV MEASUREMENTS OF β GEM

JD	RV ($\mathrm{km\,s^{-1}}$)	σ($\mathrm{km\,s^{-1}}$)
2452776.997254	0.0305	0.0088
2452776.998932	0.0191	0.0093
2452779.975062	0.0462	0.0131
2452779.979240	0.0488	0.0208
2452779.985258	0.0271	0.0232
2452780.979924	0.0372	0.0106
2452780.981672	0.0435	0.0087
2452780.983315	0.0357	0.0097
2452949.319857	0.0766	0.0070
2452949.322815	0.0811	0.0063
2452950.314238	0.0868	0.0058
2452950.317479	0.0839	0.0066
2452976.213604	0.0838	0.0060
2452976.216752	0.0881	0.0062
2453044.016184	0.1093	0.0088
2453044.020107	0.1088	0.0054
2453044.024794	0.1144	0.0055
2453044.034412	0.1115	0.0053
2453045.021024	0.1052	0.0055
2453045.023050	0.1088	0.0055
2453045.024948	0.1022	0.0049
2453046.017820	0.1011	0.0053
2453046.020088	0.0943	0.0052
2453046.021882	0.1033	0.0056
2453046.059450	0.1020	0.0064
2453046.061614	0.1021	0.0054
2453046.065468	0.1031	0.0057
2453046.094298	0.1036	0.0052
2453046.096763	0.1035	0.0055
2453046.098719	0.1011	0.0053
2453046.171921	0.0982	0.0056
2453046.174190	0.1010	0.0050
2453046.175914	0.0991	0.0054
2453047.066602	0.1082	0.0060
2453047.069021	0.1129	0.0063
2453047.071208	0.1028	0.0057
2453047.116681	0.1119	0.0049
2453047.122328	0.1083	0.0052
2453047.126171	0.1084	0.0054
2453047.189501	0.0987	0.0061
2453047.193135	0.1050	0.0068
2453047.200901	0.1036	0.0058
2453048.022841	0.1079	0.0056
2453048.024935	0.1125	0.0056
2453048.026868	0.1110	0.0057
2453048.098092	0.1091	0.0055
2453048.100129	0.1050	0.0055
2453048.103902	0.1018	0.0061
2453048.146955	0.1189	0.0059
2453048.148841	0.1147	0.0052
2453048.150693	0.1179	0.0056
2453048.218792	0.0949	0.0064
2453048.220829	0.0975	0.0054
2453048.224220	0.0924	0.0054
2453072.028116	0.1200	0.0059
2453072.031947	0.1260	0.0048
2453072.035384	0.1239	0.0057
2453096.098145	0.0941	0.0054
2453127.006614	0.0924	0.0062
2453127.011544	0.1005	0.0067

TABLE 2. CONTINUED

JD	RV (km s^{-1})	σ(km s^{-1})
2453131.000019	0.1067	0.0066
2453131.002866	0.0992	0.0068
2453131.964630	0.1013	0.0063
2453132.968116	0.0976	0.0061
2453132.970124	0.1008	0.0058
2453132.971872	0.0917	0.0065
2453301.328524	0.0142	0.0050
2453301.331522	0.0210	0.0050
2453303.379217	0.0189	0.0050
2453303.382255	0.0234	0.0048
2453303.385340	0.0114	0.0053
2453331.251540	0.0144	0.0053
2453331.255186	0.0162	0.0058
2453354.166531	0.0133	0.0059
2453354.171046	0.0031	0.0050
2453356.151683	0.0159	0.0050
2453356.154950	0.0139	0.0047
2453430.084865	0.0395	0.0059
2453430.088019	0.0391	0.0061
2453729.146160	0.1141	0.0059
2453729.150095	0.1117	0.0065
2453756.203961	0.0794	0.0044
2453758.206584	0.0815	0.0048
2453759.261126	0.0810	0.0044
2453761.143348	0.0841	0.0049
2453778.169169	0.0777	0.0055
2453778.176750	0.0783	0.0046
2453778.182224	0.0741	0.0048
2453778.974084	0.0769	0.0048
2453779.156436	0.0736	0.0049
2453779.160579	0.0770	0.0050
2453817.015301	0.0559	0.0062
2453817.019676	0.0596	0.0054
2453817.024016	0.0599	0.0051
2453819.061517	0.0526	0.0047
2453819.064858	0.0510	0.0047
2453866.996385	0.0440	0.0061
2453867.000470	0.0485	0.0058
2454027.263759	0.0266	0.0048
2454027.267405	0.0258	0.0051
2454123.058536	0.0749	0.0048
2454123.060203	0.0725	0.0045
2454125.159519	0.0676	0.0055
2454147.201976	0.0852	0.0051
2454147.202878	0.0856	0.0050
2454207.068365	0.1133	0.0060
2454207.071478	0.1131	0.0068
2454207.074719	0.1110	0.0063
2454209.039583	0.0969	0.0057
2454209.043229	0.1008	0.0062
2454209.987917	0.1076	0.0053
2454214.021806	0.1098	0.0067
2454214.030034	0.1152	0.0073
2454214.035520	0.0989	0.0059
2454216.957633	0.0995	0.0056
2454216.958860	0.1012	0.0059
2454222.995580	0.0953	0.0059
2454222.997084	0.1067	0.0062
2454222.998589	0.1028	0.0061
2454223.000140	0.1058	0.0063
2454223.001853	0.1054	0.0059

TABLE 2. CONTINUED

JD	RV (km s^{-1})	σ(km s^{-1})
2454223.003750	0.1018	0.0059
2454223.005706	0.1021	0.0059
2454223.007708	0.1000	0.0060
2454223.009606	0.1003	0.0062
2454223.011562	0.1013	0.0062
2454223.977815	0.1056	0.0058
2454223.981322	0.1027	0.0062
2454254.976646	0.1013	0.0068
2454382.355266	0.0536	0.0065
2454382.358588	0.0409	0.0088
2454382.361797	0.0566	0.0063
2454390.381845	0.0444	0.0060
2454390.385329	0.0483	0.0054
2454390.388674	0.0441	0.0061
2454426.377938	0.0483	0.0056
2454426.379327	0.0532	0.0056
2454452.352831	0.0454	0.0055
2454452.354741	0.0507	0.0055
2454452.356095	0.0504	0.0054
2454452.357299	0.0515	0.0054
2454458.320822	0.0433	0.0058
2454458.322489	0.0459	0.0061
2454458.324306	0.0467	0.0057
2454458.326274	0.0496	0.0060
2454470.146095	0.0348	0.0055
2454470.147600	0.0370	0.0057
2454470.149070	0.0382	0.0056
2454470.150540	0.0359	0.0051
2454458.320822	0.0433	0.0058
2454458.322489	0.0459	0.0061
2454458.324306	0.0467	0.0057
2454458.326274	0.0496	0.0060
2454472.008242	0.0206	0.0083
2454472.013485	0.0470	0.0347
2454505.143681	0.0276	0.0060
2454505.145220	0.0196	0.0056
2454505.146690	0.0274	0.0056
2454505.148172	0.0263	0.0058
2454507.041386	0.0081	0.0064
2454507.047555	0.0096	0.0061
2454507.051015	0.0204	0.0064
2454507.053527	0.0112	0.0058
2454507.056085	0.0155	0.0057
2454507.058596	0.0169	0.0061