JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
38: 315 ∼ 318, 2005

OKAYAMA PLANET SEARCH PROGRAM

BUN'EI SATO
Graduate School of Science and Technology, Kobe University, 1-1 Rokkodai, Nada-ku, Kobe 657-8501, Japan
E-mail: satobn@kobe-u.ac.jp
(Received February 1, 2005; Accepted March 25, 2005)

ABSTRACT

We have carried out a precise Doppler survey of G-type giants aiming to unveil the properties of planetary systems in intermediate-mass stars (1.5–5$M_\odot$). G-type giants are promising targets for Doppler planet searches around massive stars, because they are slow-rotators and have many sharp absorption lines in their spectra and their surface activities are relatively low in contrast to their younger counterparts on the main-sequence (B–A stars). We are now monitoring radial velocities of about 300 late G-type (including early K-type) giants using HIgh Dispersion Echelle Spectrograph (HIDES) at Okayama Astrophysical Observatory. We have achieved a Doppler precision of about 6–7 m/s over a time span of 3 years using an iodine absorption cell. We found that most of the targets have radial velocity scatters of $\sigma \sim$ 10–20 m s^{-1} over 1–3 years, with the most stable reaching levels of 6–8 m s^{-1}. Up to now, we have succeeded in discovering the first extrasolar planet around a G-type giant star HD 104985, and also found several candidates showing significant radial velocity variations, suggesting the existence of stellar and substellar companions. Observations have continued to establish their variability.

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

I. INTRODUCTION

Since the discovery of the first extrasolar planet in 1995, more than 130 planetary candidates have been revealed around solar-type stars by precise measurements of stellar radial velocity variations. On the other hand, planets around other types of stars have been less extensively surveyed and theoretically investigated. Planetary systems in more massive ($\gtrsim 1.5M_\odot$) stars are particularly important for constructing planet formation theory because in those stars the evolution time scale is much shorter, then proto-planetary disks also have shorter lifetimes (<a few Myr; Haisch et al. 2001a, 2001b), which means that time allowed for planet formation is also much shorter. Therefore, the properties of giant planets around such stars, if they exist, would constrain the time scale of planet formation and verify the current planet formation theory (e.g., Pollack et al. 1996). Little is known, however, about planetary systems in massive stars because precise radial velocity measurements are difficult when such stars are on the main-sequence (early-type stars) due to the lack of appropriate absorption lines in their spectra.

The G-type giants, massive stars in evolved stages, are promising targets for Doppler planet searches around massive stars, because they usually have many sharp absorption lines in their spectra while the stars themselves remain relatively stable against pulsation and surface activities. Previous studies showed that many late G-, and early K-type giants typically have small intrinsic radial velocity dispersions of 10 ∼ 20 m s^{-1} (Frink et al. 2001; Sato et al. 2005), and this level of stability in radial velocity is small enough to detect massive planets in orbits close to central stars. In fact, several planetary companions have been discovered around such stars during the last few years (Frink et al. 2002; Setiawan et al. 2003a; Setiawan 2003b; Sato et al. 2003; Mitchell et al. 2004).

On these grounds, since 2001, we have been carrying out a precise Doppler survey of late G-type (including early K-type) giants to search for planets around intermediate-mass stars (1.5–5$M_\odot$) at Okayama Astrophysical Observatory (OAO), NAOJ in Japan. The survey initially began with about 60 targets and was extended to include 180 stars in the second year. Since 2004, about 300 stars have been under survey. Up to now, we have succeeded in discovering the first extrasolar planet around a G-type giant star HD 104985 (Sato et al. 2003). We here report the results of our survey obtained in these 3 years and discuss future prospects.

II. OKAYAMA PLANET SEARCH PROGRAM

(a) Program Stars

Our sample contains about 300 late G or early K giants, ranging in color index $B - V$ from 0.6 to 1, selected from the Hipparcos catalogue (ESA 1997). Most giants in this range are known to be amongst the stable stars in photometry (Henry et al. 2000) and in radial velocity (Frink et al. 2001; Sato et al. 2005). We also constrain our sample in absolute magnitude

Proceedings of *the 6th East Asian Meeting of Astronomy*, held at Seoul National University, Korea, from October 18-22, 2004.

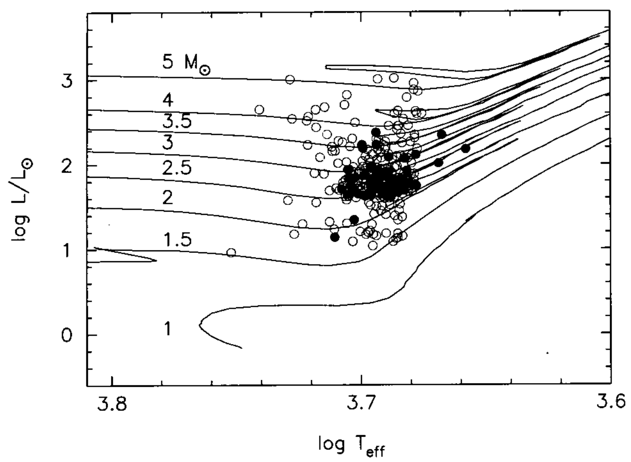

Fig. 1.— H–R diagram of all the targets in the Okayama Planet Search Program. The 57 primary targets that were observed in 2001–2003 are plotted by filled circles and the others are plotted by open ones. Evolutionary tracks for solar-metallicity stars, taken from Girardi et al. (2000), are also shown. Stellar radii of the selected targets are estimated to be typically $10R_{\odot}$.

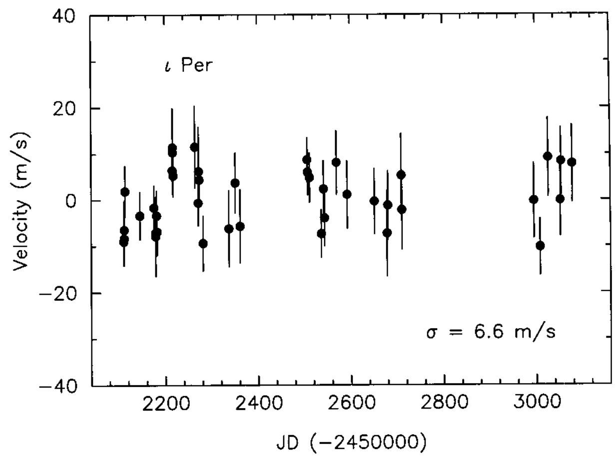

Fig. 2.— Radial velocities of ι Per observed with HIDES. The typical measurement error is 5–7 m s^{-1}.

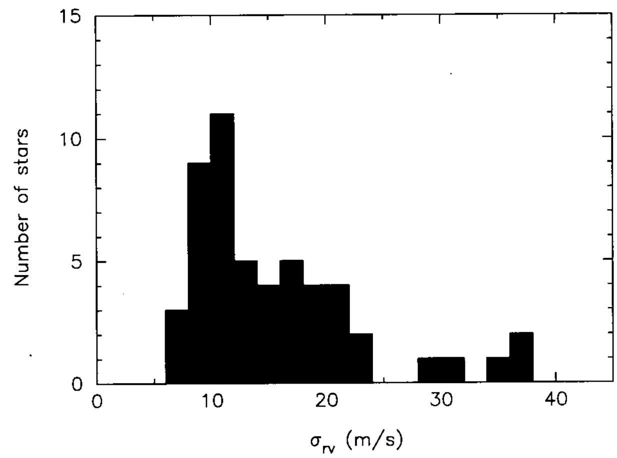

Fig. 3.— Histogram of the radial velocity dispersion of 57 primary targets that were observed in 2001–2003. Five stars with dispersion larger than 50 m s^{-1} are not shown.

M_V from −3 to 2 to include stars with masses from about 1.5 to $5M_{\odot}$. All of the stars are north of declination −25° to be observed from OAO, and are brighter than $V = 6$ to attain a sufficient signal-to-noise (S/N) ratio. Stars known as spectroscopic binaries or having companions within an angular separation of about 10″ are excluded due to difficulties in the observation and analysis. Known photometric variables are also excluded based on the results of Hipparcos photometry. Figure 1 shows the positions of our target stars on the H–R diagram.

(b) Observation and Radial Velocity Analysis

For radial velocity measurements, we use HIgh Dispersion Echelle Spectrograph (HIDES; Izumiura 1999) and an iodine absorption cell (I_2 cell; Kambe et al. 2002) equipped at the coude focus of the 1.88 m reflector at OAO. We can achieve a spectral resolution of $R \sim 70000$ for the slit width of 200 μm (0″.76) corresponding to 3.5 pixels sampling. The wavelength region is set to cover 5000–6200Å, including the region of 5000–5800Å, where many deep and sharp I_2 absorption lines exist. We can typically obtain S/N>200 pix^{-1} for a $V < 6$ star with an exposure time shorter than 30 min.

We have developed our own computer code for the analysis of I_2-calibrated data, which is based on the works of Butler et al. (1996) and Valenti et al. (1995) and is optimized for HIDES. In the I_2-technique, an I_2- superposed stellar spectrum (star+I_2) is modeled as a product of a high-resolution stellar and an I_2 template spectrum convolved with the spectrograph instrumental profile (IP), which is modeled by combining Gaussian profiles. To obtain a stellar template spectrum, we have devised a new method to determine IP free stellar spectrum from several to tens of star+I_2 spectra (Sato et al. 2002). In figure 2, we show the radial velocities of ι Per (HD 19373, V = 4.05, G0 V), a radial velocity standard, observed with HIDES. It shows that we have achieved a Doppler precision of 6-7 m s^{-1} over a time span of about 2 years.

III. RESULTS

(a) Radial Velocity Stability of G-Type Giants

Figure 3 shows the histograms of the resulting radial velocity dispersions for the 57 stars of our primary sample that were observed in 2001–2003. The typical number and duration of observations for these stars are 10 and 2 years, respectively. The distribution of the radial velocity dispersions has a peak at around $\sigma \sim 10$ m s^{-1}. About 60% of the targets are stable in radial

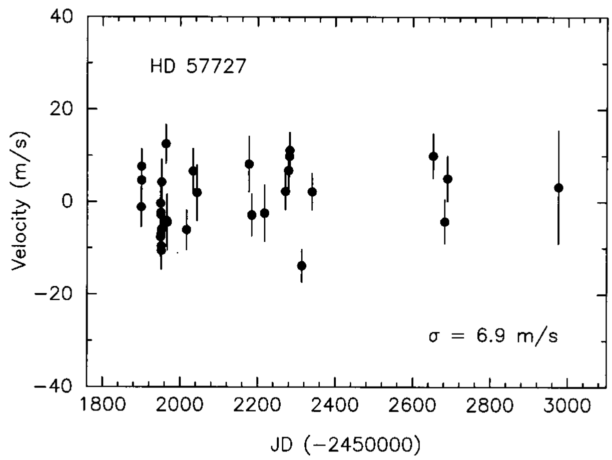

Fig. 4.— Radial velocities of HD 57727 (G8III) showing small radial velocity dispersion.

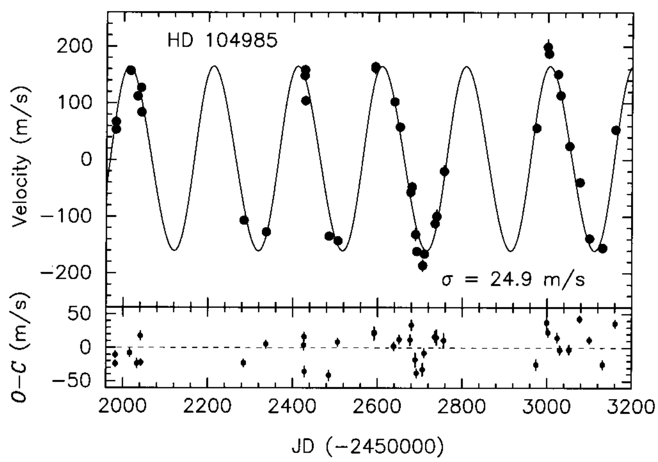

Fig. 5.— *Top*: Radial velocities of HD 104985 (*dots*). The best-fit Keplerian orbit is also shown (*solid line*). *Bottom*: Residuals to the Keplerian fit.

velocity to a level of $\sigma < 15$ m s^{-1}, and about 90% have $\sigma < 30$ m s^{-1} over a time span of 1–3 years. The most stable ones reach levels of $\sigma = 6$–8 m s^{-1}. An example of such stable giants in radial velocity is shown in figure 4. We can detect planets with $m_2 \sin i \gtrsim 1 M_J$ at $a \sim 1$ AU around such stable stars. This level of variability of G giants is lower than that of K giants, which typically show $\sigma \sim 20$ m s^{-1} (Frink et al. 2001).

(b) Planetary Candidates

HD 104985 ($V = 5.78$, G9 III) was reported in a previous paper to be the first planet-bearing star discovered from our survey (Sato et al. 2003). After the discovery, observations have continued to determine the orbital parameters more precisely and to find other periodicity. We present the latest results of radial velocity measurements of HD 104985 in figure 5. The best-fit Keplerian orbit is also shown in the figure and its updated parameters are listed in table 1. The radial velocity variability of the star is well fitted by a nearly-circular orbit with a period $P = 198.3 \pm 0.2$ days, a velocity semiamplitude $K_1 = 163 \pm 2$ m s^{-1}, and an eccentricity $e = 0.06 \pm 0.01$. The period of 198 days in radial velocity has been present and coherent for the past 3 years. The small eccentricity of HD 104985 b is remarkable while currently known planets around K giants have large eccentricities. The rms scatter of the residuals to the Keplerian fit is 24.9 m s^{-1}, which is slightly larger than the typical intrinsic velocity scatter of $\sim$10 m s^{-1} for these types of stars, but we have not found any significant periodicities or long-term trends in the residuals.

We previously reported the mass of HD 104985 to be 1.6 $M_\odot$ in Sato et al. (2003). This value, however, was based on the metallicity of [Fe/H]=-0.35 which was a result of our preliminary determination. Takeda et al. (2005) updated the [Fe/H] and the mass for the star, -0.15 and 2.3 $M_\odot$, respectively. By adopting this value, we obtained a mass for companion $m_2 \sin i = 8.1$ M_J and a semimajor axis $a = 0.88$ AU.

Table 1.
Updated orbital parameters for HD 104985

Parameter	Value
P (days)	198.3±0.2
K_1 (m s^{-1})	163±2
e	0.06±0.01
ω (deg)	283±13
T_p (JD−2,450,000)	1975±7
$a_1 \sin i$ (10^{-3}AU)	2.96±0.03
$f_1(m)$ ($10^{-8} M_\odot$)	8.8±0.3
$m_2 \sin i$ (M_J)	8.1
a (AU)	0.88
N_{obs}	36
rms (m s^{-1})	24.9
Reduced χ	3.7

At present, the number of stars we have monitored for longer than 1 year reaches about one hundred. About 10% of them (not including HD 104985) apparently show radial velocity variations with periods of 180$\sim$1000 days and amplitudes of 30$\sim$100 m s^{-1}. If these were due to orbital motions, their companions would have masses of $3 \sim 10 M_J$ and semimajor axes of $0.8 \sim 2.5$ AU. Periodic radial velocity variations with amplitudes up to 100 m s^{-1} are rarely shown in late G giants, suggesting that such variations are not caused by stellar intrinsic variability such as pulsation or rotational modulation but by orbital motion. On the other hand, as for variations of $\sim$ 30 m s^{-1}, it is difficult to distinguish their causes at this stage because the amplitudes are comparable to the level of the intrinsic radial velocity scatters for G giants. Further observations combined with monitoring line profile variations would help us to discriminate planetary hypothesis from stellar intrinsic variability.

IV. SUMMARY AND FUTURE PROSPECTS

Since 2001, we have carried out a precise Doppler survey of 300 late G (and early K) giants using HIDES at OAO to search for planets around intermediate-mass stars (1.5–5$M_{\odot}$). In this paper, we have reported the results of our survey obtained in these 3 years.

Most of the 57 targets of our primary sample showed radial velocity dispersions of $\sigma \sim 10$ m s^{-1}, with the most stable reaching levels of 6–8 m s^{-1} over a time span of 1–3 years. We can detect planets with $m_2 \sin i \gtrsim 1 M_J$ at $a \sim 1$ AU around such stable stars. This level of variability of G giants is lower than that of K giants, which typically show $\sigma \sim 20$ m s^{-1}.

Up to now, we have discovered one extrasolar planet orbiting G9 III giant star HD 104985. Its mass and semimajor axis are estimated to be $m_2 \sin i = 8.1 M_J$ and 0.88 AU, respectively, and it resides in a nearly-circular orbit with an eccentricity of 0.06. We also identified several candidates showing periodic radial velocity variations, suggesting the existence of stellar and substellar companions. We have continued observations to establish their variability.

Assuming the rate of occurrence of giant planets to be about 5%, we would expect to discover about 15 planets in the current 300 targets. However, to fully discuss the statistical properties of planetary systems, we need to find at least several tens to hundred planets. For this purpose, in 2005, we will launch a new survey targeting more than 100 G, K giants with $V > 6$ by establishing international collaborations between Chinese, Korean and Japanese groups (see the article by Dr. H. Izumiura in this issue). We try to double the current number of survey targets and to boost the planet search program around intermediate-mass stars.

REFERENCES

Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S., 1996, PASP, 108, 500

ESA., 1997, The Hipparcos and Tycho Catalogues (Noordwijk, Netherlands: ESA)

Frink, S., Quirrenbach, A., Fischer, D., Röser, S., & Schilbach, E., 2001, PASP, 113, 173

Frink, S., Mitchell, D. S., Quirrenbach, A., Fischer, D. A., Marcy, G. W., & Butler, R.P., 2002, ApJ, 576, 478

Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C., 2000, A&AS, 141, 371

Haisch, K. E., Jr., Lada, E. A., & Lada, C. J., 2001a, AJ, 121, 2065

Haisch, K. E., Jr., Lada, E. A., & Lada, C. J., 2001b, ApJ, 553, L153

Henry, G. W., Fekel, F. C.,Henry, S. M., & Hall, D. S., 2000, ApJS, 130, 201

Izumiura, H., 1999, in Proc. 4th East Asian Meeting on Astronomy, ed. P.S. Chen (Kunming: Yunnan Observatory), 77

Kambe, E. et al., 2002, PASJ, 54, 865

Mitchell, D. S., Frink, S., Quirrenbach, A., Fischer, D., Marcy, G. W., & Butler, R. P., 2004, BAAS, 35, 1127

Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y., 1996, Icarus, 124, 62

Sato, B., et al., 2003, ApJ, 597, L157

Sato, B., Kambe, E., Takeda, Y., Izumiura, H., & Ando, H., 2002, PASJ, 54, 873

Sato, B., Kambe, E., Takeda, Y., Izumiura, H., Masuda, S., & Ando, H., 2005, PASJ, 57, in press

Setiawan, J., et al., 2003a, A&Ap, 398, L19

Setiawan, J., 2003b, in Towards Other Earths, DARWIN/TPF and the Search for Extrasolar Terrestrial Planets, held in Heidelberg, Germany, 22-25 April, ESA SP-539, ed. M. Fridlund, & T. Henning, 595

Takeda, Y, Sato, B., Kambe, E., Izumiura, H., Masuda, S., & Ando, H., 2005, PASJ, 57, in press

Valenti, J.A., Butler, R.P., & Marcy, G. W., 1995, PASP, 107, 966