EXOPLANETS: Detection, Formation and Dynamics
Proceedings IAU Symposium No. 249, 2007
Y.-S. Sun, S. Ferraz-Mello & J.-L. Zhou, eds.

doi:10.1017/S1743921308016360

A Korea-Japan planet search program: Current status and discovery of a brown dwarf candidate

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Abstract. Since 2005, we have been carrying out a precise radial velocity survey of about 190 intermediate-mass (1.5-5 $M_\odot$) G and K giants at Bohyunsan Optical Astronomy Observatory (BOAO) in Korea and Okayama Astrophysical Observatory (OAO) in Japan, which aims to reveal statistical properties of planetary systems around intermediate-mass stars. We have finished the first screening of 120 stars so far and have identified 5 candidates with large periodic radial velocity variations. One of the candidates turned out to be orbited by a brown dwarf mass companion with minimum mass of 37.6 M_{Jup} and semimajor axis of 1.71 AU. The primary star has a mass of 3.9 $M_\odot$, which ranks among the most massive stars with substellar companions. Our discovery may support the current view obtained from results of planet searches around intermediate-mass stars that massive substellar companions tend to form around massive stars.

Keywords. stars: low-mass, brown dwarfs, techniques: radial velocities

1. Introduction

To date, more than 200 exoplanets have been detected around solar-type stars by precise Doppler surveys. These surveys have unveiled various statistical characteristics of the planets. On the other hand, only 10 planets have been discovered around intermediate-mass stars (1.5-5 $M_\odot$) and their statistical properties have not been yet clear. Planetary systems around such massive stars are particularly important for constructing planet formation theories because they can constrain key processes of the planet formation such as dependence on host star's mass (probably related with mass of proto-planetary disk), role of radiation of central stars, and timescale of planet formation. However, early-type stars (B-A dwarfs), intermediate-mass stars on the main sequence, are not suitable for precise radial velocity survey due to fewer metallic absorption lines in their spectra and higher surface activity. Late G and early K type giants, intermediate-mass stars in the evolved stages, are promising targets for this purpose because they have many sharp absorption lines in their spectra and their surface activity is relatively low compared to early-type stars and more evolved late K and M type giants.

So far, radial velocity surveys of intermediate-mass stars (e.g. Johnson *et al.* 2006, Sato *et al.* 2007, Niedzielski *et al.* 2007) have revealed some properties of substellar companions around them. For example, frequency of massive substellar companions is higher than that of solar-type stars (Lovis & Mayor 2007, Johnson *et al.* 2007), and many massive host stars have lower metallicity than typical one of solar-type host stars (e.g. Sato *et al.* 2003). These properties seem to be not similar to those of solar-type stars and such different properties should be explored by further studies. In the case of solar-type stars, a "brown dwarf desert" is widely known as a paucity of substellar companions falling in the brown dwarf mass region (13-80 M_{Jup}) (Marcy & Butler 2000, Halbwachs *et al.* 2000, Grether & Lineweaver 2006), which suggests distinct formation mechanisms between planets and stellar companions. To uncover whether a brown dwarf desert also exist around intermediate-mass stars will give us a clue to understand formation mechanism of planets around them.

2. Korea-Japan Planet Search Program

We are monitoring our targets using the 1.8 m telescope at BOAO with Bohyunsan Optical Echelle Spectrograph (BOES, $R = \lambda/\Delta\lambda = 50000$, 3500Å-10500Å), which is a fiber-fed high resolution echelle spectrograph (Kim *et al.* 2007) and the 1.88 m telescope at OAO with HIgh Dispersion Echelle Spectrograph (HIDES, R=65000, 5000Å-6100Å) installed at the coude focus of the telescope (Izumiura 1999). For precise radial velocity measurements, an iodine absorption cell (I2 cell) is installed at the optical path in front of the fiber or slit of each spectrograph (Kim *et al.* 2002, Kambe *et al.* 2002). We also take stellar spectra without I2 cell for abundance analysis. Radial velocities are derived by using Sato *et al.* (2002)'s code which models an I2-superposed stellar spectrum with high resolution stellar and iodine templates and reproduced instrumental profiles of the spectrographs. We have achieved long term radial velocity precisions of $\sim$ 11 m/s and $\sim$

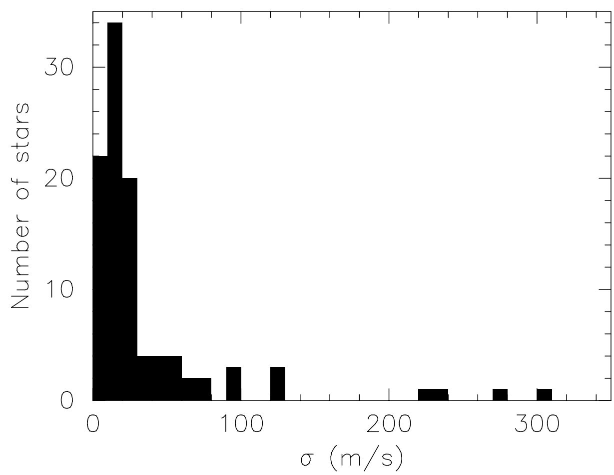

Figure 1. Velocity RMS of 116 BOAO & OAO targets observed more than three times for 2.5 years.

6-7 m/s with BOES and HIDES, respectively, over a time span of 2.5 years during the project. A Korea-Japan planet search program has been conducting a precise Doppler survey of about 190 G and K giants at BOAO in Korea and OAO in Japan since 2005. This joint planet search program is an extended version of on-going OAO planet search program (Sato *et al.* 2005) and a part of the international collaborations between Korea, China and Japan (East-Asian Planet Search Network, EAPSNet, Izumiura 2005) aiming to obtain the properties of planetary systems around intermediate-mass stars by surveying a total of "1000" giant stars for planets.

3. Current status and Orbital solution of a brown dwarf companion

Up to now, we observed about 120 targets more than three times. Seventeen of the targets exhibited large radial velocity variations with amplitudes of 50 m/s - 350 m/s and five of them showed probable periodic variations (See Figure 1).

One of such targets clearly shows large periodic radial velocity variations as seen in Figure 2. Low surface activity of this star favors an orbital motion as the cause of the observed variability. On the basis of Keplerian orbital fit, we obtained a velocity semi-amplitude of 413.5 ± 2.6 m/s, period of 410.5 ± 0.6 days and eccentricity of 0.082 ± 0.007. Adopting a host star's mass of 3.9 ± 0.4 $M_\odot$, which was estimated from evolutionary track and fundamental stellar parameters of $L = 251 \pm 95$ $L_\odot$, $T_{eff} = 5083 \pm 103$ K, and [Fe/H] = 0.04 ± 0.18, we obtained a minimum mass for the companion $m_p \sin i = 37.6 \pm 2.6$ M_{Jup} and a semimajor-axis of $a = 1.71 \pm 0.06$ AU. If we assume the orbit is randomly oriented, there is a 12% chance that the true mass exceeds 80 M_{Jup} ($i \geqslant 28°$).

4. Summary

We have been carrying out a precise redial velocity survey of G and K giants at BOAO and OAO and discovered a brown dwarf mass companion together with some planetary candidates so far. This brown dwarf companion is the forth one among those discovered around intermediate-mass giants. The host star has a mass of 3.9 $M_\odot$, which is one of the most massive stars harboring substellar companions. Three stars with masses of larger

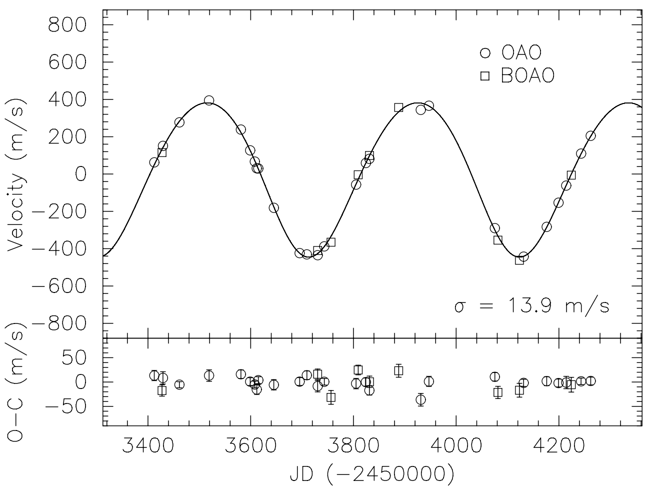

Figure 2. Radial velocities and orbital fit of a star with a brown dwarf candidate from BOAO (open squares) and OAO (open circles). O-C indicates difference between each observational point and orbital curve.

https://doi.org/10.1017/S1743921308016360 Published online by Cambridge University Press

than 3 $M_\odot$ are currently known to harbor substellar companions (Hatzes *et al.* 2005, Lovis & Mayor 2007, this work) and all the companions have brown dwarf mass. The result supports the current view that more massive substellar companions tend to form around more massive stars (Lovis & Mayor 2007, Johnson *et al.* 2007).

So far, we have detected two brown dwarf mass companions (Liu *et al.* 2008 and this work) among a total of about 500 targets from OAO and BOAO-OAO surveys. The current detection rate of brown dwarf companion in our sample is thus estimated to be 0.4 %, which seems to be comparable to that of less than 1% for solar-type stars (Marcy & Butler 2000, Grether & Lineweaver 2006). It is still unclear, however, whether a brown dwarf desert also exists among intermediate-mass stars. Since less massive planets are normally difficult to detect around evolved giants due to their larger intrinsic radial velocity variability (up to 10 - 20 m/s), a mass distribution of planetary mass companions around them has not been well established yet. Further investigation of a mass distribution of substellar companions is required to elucidate formation mechanism of planets and brown dwarfs around massive stars.

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