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Radial-Velocity Searches for Exoplanets in East Asia

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Abstract. Hundreds of extrasolar planets have been discovered around various types of stars by various techniques during the past decade. Among them precise radial velocity measurements for stars are fundamental technique to detect and confirm exoplanets. In this paper activities in East-Asian region in this research field are introduced: East-Asian Planet Search Network, which is a network searching for planets around evolved intermediate-mass stars, and Subaru/IRD project, which will search for habitable planets around M-type dwarfs using infrared radial-velocity method.

Keywords. radial velocity, exoplanets, GK giants, M dwarfs

1. Introduction

Precise measurements of stellar radial velocity (RV) variations are powerful technique to detect extrasolar planets, that is, planets orbiting stars other than the Sun. The technique tries to detect tiny wobble of star in RV due to the reflex motion induced by orbiting planets. Since the first discovery of an extrasolar planet, the RV techniques have uncovered more than 500 extrasolar planets around various types of stars and the planets show remarkable diversity in their properties (e.g. Udry & Santos 2007). The RV measurement precision has now reached to less than 1 m s^{-1}, which enables us to detect planets of a few Earth-masses in short-period orbits (e.g. Pepe *et al.* 2011). From the RV planet surveys, we learned that planets are almost commonly exist around solar-type stars. Based on the latest statistics, about 70% of nearby solar-type stars have at least one planet within orbital period of 10 yr and less massive planets are more abundant than massive giant planets (Mayor *et al.* 2011; Howard *et al.* 2011a). The occurrence rate of giant planets increases with stellar mass from 2% around M-type dwarfs to 20% around A-type dwarfs (Johnson *et al.* 2010), which may be related with mass of proto-planetary disks, but on the contrary that of super-Earths tend to increase toward M dwarfs up to >30% (Bonfils *et al.* 2013). Transit surveys also played important roles in the recent explosive discoveries of planets. Among them, the *Kepler* unveiled more than 2000 planet candidates down to approximately Earth-sized (Batalha *et al.* 2013), some of which are located in habizable zones (e.g. Borucki *et al.* 2012), and indicates that small planets are abundant around solar-type stars and the occurrence rate rises substantially with decreasing stellar mass; the occurrence rate of 2–4$R_\oplus$ planets around M0 dwarfs is about 25%, while that around F dwarfs is 5% at most (Howard *et al.* 2012).

These studies of extrasolar planets, however, have primarily focused on planets around FGK-type dwarfs. On the other hand, those around lower-mass stars, such as ML-type dwarfs, have not been well explored yet, although many small and less massive planets are expected around them as described above, because they are intrinsically faint in visible wavelength even using large-aperture telescopes such as Keck and Subaru. Therefore, the current RV planet searches are limited to stars more massive than M3-type dwarfs ($\gtrsim$0.3 $M_\odot$). Also, planets around higher-mass stars than the Sun have not been well explored either because those on the main sequence, BA-type dwarfs, are not suitable to RV planet searches due to the lack of appropriate absorption lines in their spectra. However, from surveys targeting GK-type giants, high-mass stars in evolved stages, planetary systems around massive stars have begun to be uncovered (e.g. Sato *et al.* 2003).

In this paper, research activities in the filed of RV planet searches in East-asian region are introduced: the East-Asian Planet Search Network, which is a network searching for planets around evolved intermediate-mass stars, and Subaru/IRD project, which will search for habitable planets around M-type dwarfs using infrared RV method.

2. East-Asian Planet Search Network (EAPSNet): Searching for Planets around Evolved Intermediate-mass Stars

2.1. *Overview*

The East-Asian Planet Search Network (EAPSNet; Izumiura 2005; Fig 1) is an international network on RV planet searches between 2m-class telescopes in China, Korea, and Japan, which started collaborative observations in 2005. Current main aim of the network is to search for giant planets orbiting around evolved intermediate-mass stars.

To derive properties of planetary systems in more massive stars than the Sun is important for constructing planet formation theory because the different properties of the central stars such as temperature, luminosity, life time, initial disk mass and so on can constrain key factors (timescale, role of radiation, dependence on disk mass, etc.) of planet formation. Little had been known, however, about planetary systems in massive (especially $\geqslant 2M_\odot$) stars because precise RV measurements are more difficult for such stars when they are on the main-sequence (i.e. BA-type dwarfs) due to the lack of appropriate absorption lines in their spectra and thus planets around such stars have been less intensively surveyed compared to those around lower-mass stars.

From these view points, planets around intermediate-mass giants and subgiants have been intensively surveyed over the past several years (e.g. Sato *et al.* 2012). They are

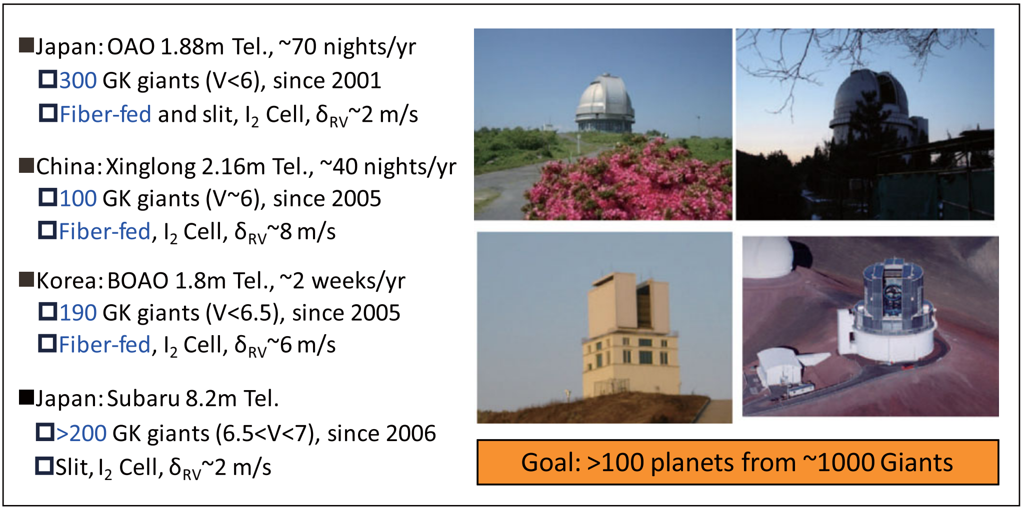

Figure 1. Telescopes used for RV planet searches around evolved intermediate-mass stars in East Asia.

evolved counterparts of BA-type dwarfs and are suitable targets for RV planet searches with many sharp absorption lines in their spectra and relatively low stellar activity. Actually, more than 50 substellar companions to such evolved intermediate-mass stars have been already found and they have shown remarkable properties: higher occurrence rate of giant planets for intermediate-mass subgiants than that for lower-mass stars (Johnson *et al.* 2007b; Bowler *et al.* 2010), larger typical mass of giant planets (Lovis *et al.* 2007; Omiya *et al.* 2009), lack of inner planets with semimajor axes <0.6 AU (Johnson *et al.* 2007a; Sato *et al.* 2008; Niedzielski *et al.* 2009), and lack of metal-rich tendency in planet-hosting giants (Pasquini *et al.* 2007; Takeda *et al.* 2008). All these statistical properties should be confirmed by a larger number of samples.

Since 2001, an RV planet search program targeting intermediate-mass (1.5–5$M_\odot$) 300 GK giants has been carried out at Okayama Astrophysical Observatory (OAO) in Japan. Also, in order to further extend the survey, an international consortium between Chinese, Korean, and Japanese researchers using 2m class telescopes in the three countries has been established. A total of about 600 GK giants are now under survey by the consortium and so far a total of 20 planets and 6 brown dwarf candidates have been discovered from the survey. Here the latest results from the consortium are presented.

2.2. *Okayama*

The Okayama Planet Search Program started in 2001 using 1.88m telescope and a high dispersion spectrograph at OAO. An iodine absorption cell is used for precise RV measurements and about precision of 2–4 m s^{-1} has been achieved (Kambe *et al.* 2008; Sato *et al.* 2012). About 300 GK giants brighter than $V = 6$ have been monitored, and 3 brown dwarfs and 17 planets have been discovered so far. Fig 2 shows one of the latest discoveries from OAO. The planet O CrB b is one of the least massive planets ever discovered to intermediate-mass giants (Sato *et al.* 2012). Basically it is difficult to detect less massive planets than about 2 $M_{\rm J}$ around giants because of the larger stellar "jitter" up to amplitude of 10–20 m s^{-1}. However, the detection of O CrB b demonstrates that it is still possible to detect such less massive planets around GK giants by high-cadence observations. How low mass planets are detectable around giants? Fig 3 shows RV variations of the G giant star η Her (2.4 $M_\odot$; Ando *et al.* 2010). The RV variations are dominated by solar-type oscillations with a period of $\sim$ 3–4 hours and an amplitude of $\sim$ 10 m s^{-1}, but the variations can be cancelled out down to $\lesssim$2 m s^{-1} by taking average over one night. Around such a star, even super-Earth class planets are detectable if they are in short-period orbits.

2.3. *Xinglong*

The Xinglong Planet Search Program started in 2005 within a framework of international collaboration between Chinese and Japanese researchers. The program has mainly monitored about 100 GK giants with $V \sim 6$ using 2.16m telescope, high dispersion spectrograh, and an iodine absorption cell in China (Liu *et al.* 2008). Originally the RV measurement precision at Xinglong was 30–40 m s^{-1} because of the relatively low wavelength resolution and small wavelength coverage of the old spectrograph. However, the precision has now been improved to $\sim$8 m s^{-1} by the replacement of the spectrograph. The Xinglong station has discovered 2 brown dwarfs and 1 planet so far in collaboration with OAO. Fig 4 shows the latest discovery of a brown dwarf mass companion to the intermediate-mass giant HD 175679 from observations at Xinglong and OAO (Wang *et al.* 2012).

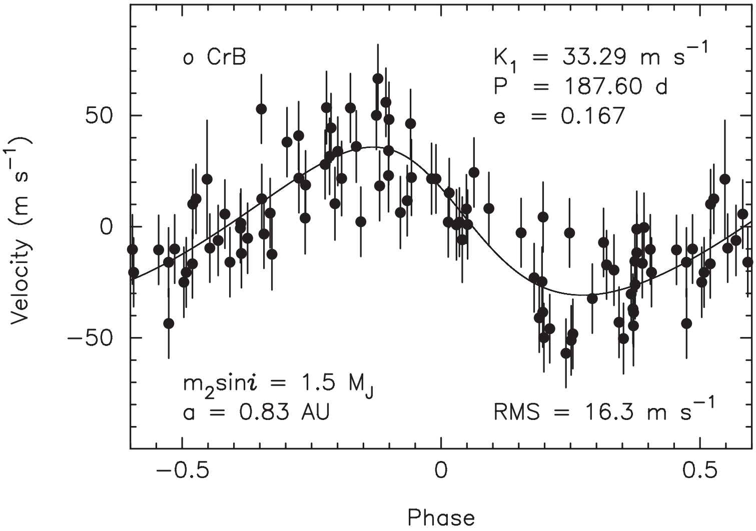

Figure 2. Phased RV curve for o CrB (K0 III), which hosts a giant planet. This is one of the least massive planets ever discovered around clump giants. The observations were made at OAO (Sato *et al.* 2012).

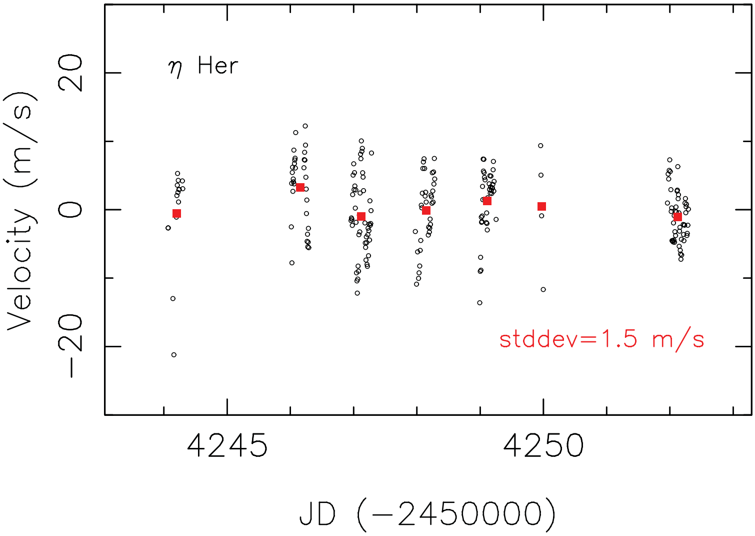

Figure 3. RV variations of the G7.5IIIb star η Her (open circles; Ando *et al.* 2010). Filled squares are binned RVs over one night, which shows RV scatters of $\sigma_{RV} = 1.5$ m s^{-1} over a period of about 8 days.

2.4. *Bohyunsan*

About 190 GK giants with $V \sim 6.5$ have been monitored at Bohyunsan Optical Astronomy Observatory (BOAO) in Korea and OAO in the framework of collaboration between Korean and Japanese researchers since 2005. The 1.8m telescope, high dispersion spectrograph, and iodine absorption cell are used for precise RV measurements, and RV precision of $\lesssim$10 m s^{-1} has been achieved using these instruments (Omiya *et al.* 2012). One brown dwarf and 1 planetary companion have been discovered so far in this collaboration. Fig 5 shows the latest discovery of a planetary companion to the intermediate-mass giant HD

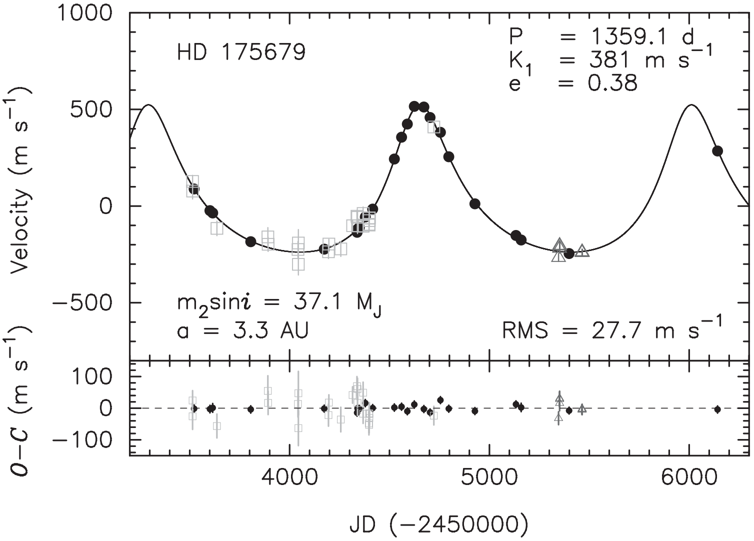

Figure 4. RVs for the G8 III giant HD 175679, which hosts a brown dwarf mass companion (Wang *et al.* 2012). The observations were made at Xinglong (open squares and triangles) and OAO (filled circles).

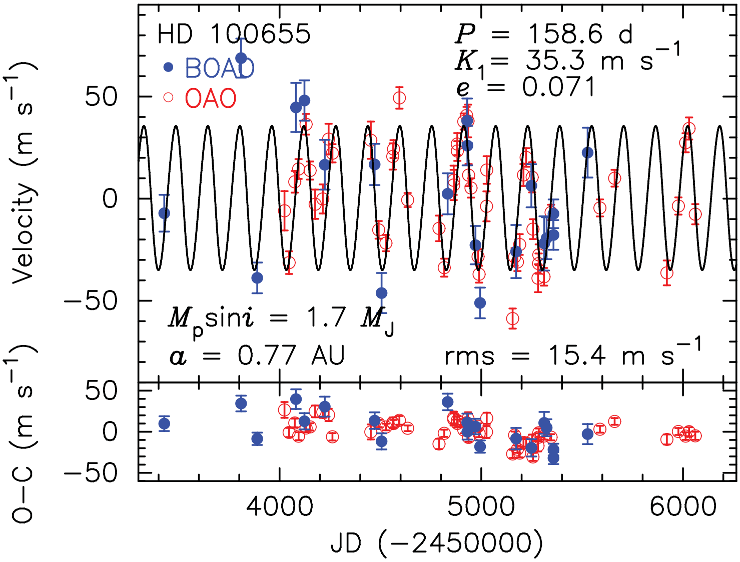

Figure 5. RVs for the G9 III giant HD 100655, which hosts a $1.7M_J$ planet (Omiya *et al.* 2012). The observations were made at BOAO (filled circles) and OAO (open circles).

100655, which is one of the least massive planet discovered around intermediate-mass clump giants. At BOAO, another planet search program targeting KM giants is also going on led by Han *et al.*, which has discovered 3 planetary companions to K giants and 2 ones to M giants (e.g., Han *et al.* 2010; Lee *et al.* 2013).

2.5. *Subaru*

The Subaru program is mainly devoted to initial screening of planet-hosting candidates using 8.2m Subaru telescope. Thanks to the large aperture of Subaru hundreds of stars

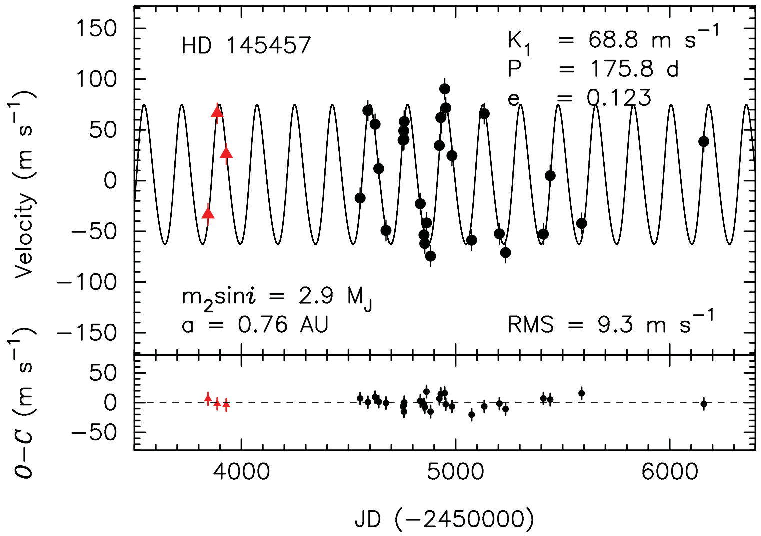

Figure 6. RVs for the K0 III giant HD 145457, which hosts a $2.9M_J$ giant planet (Sato *et al.* 2010). The observations were made at Subaru (triangles) and OAO (circles).

can be observed per night, which is quite efficient to identify stars showing large RV variations. The basic strategy is to observe each star three times every 1–2 months for the first screening and then conduct intensive follow up observations for the planet-hosting candidates using 2m-class telescopes in EAPSNet. For this purpose, the Subaru targets are typically brighter than $V = 7$, which are barely observable using 2m-class telescopes with RV precision better than 10 m s^{-1}. Fig 6 shows one of the latest discoveries from Subaru followed by OAO; a planetary mass companion to the G-type giant HD 145457 (Sato *et al.* 2010).

2.6. *Other*

Collaborative surveys for planets around evolved intermediate-mass stars have expanded as described above. In 2007 Turkish, Russian, and Japanese researchers started an RV planet search program targeting 50 GK giants using 1.5-m Russian-Turkish Telescope (RTT150), high dispersion spectrograph, and an iodine absorption cell at TUBITAK National Observatory in Turkey. Currently an RV precision of 10 m s^{-1} was achieved using these systems (Yilmaz *et al.* 2013).

3. Subaru/IRD Project: Searching for Habitable Planets around M dwarfs

Considering that M-dwarfs are the most numerous stars in the Galaxy (e.g. Covey *et al.* 2008), it can be said that we have not yet known about the vast majority of the planets in the Galaxy. Focusing planet searches on such lower mass stars offers number of benefits. The lower mass of these stars causes a much stronger dynamical response to any orbiting planet and the habitable zone is brought closer to the central stars thanks to their lower luminosity (Selsis *et al.* 2007), which makes the stars promising targets to search for “habitable planets”. Fig 7 shows the velocity amplitude of the host star imparted by the orbiting planet in habitable zone. While the velocity amplitude of the Sun caused by the Earth is only 10 cm s^{-1}, a habitable earth-mass planet around a 0.1M$_\odot$ star can impart 20 times larger velocity variations of the host star. Short-period

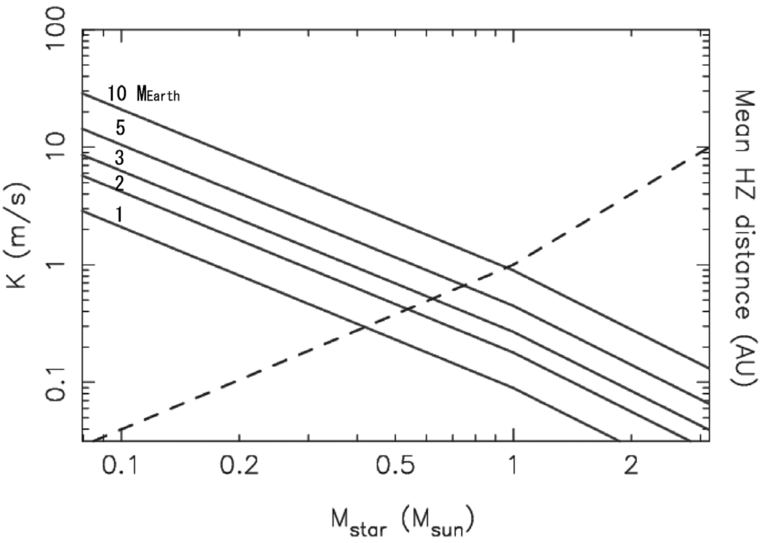

Figure 7. Velocity semiampliutde imparted by a habitable planet around various mass stars.

planets are favorable targets for RV planet searches and have a much higher transit probability, thus facilitating the measurement of planetary radii or even atmospheric composition from transit and eclipse spectroscopy. The discovery of a possibly habitable 'Super-Earth' around the early-M dwarf GJ 581 (Mayor *et al.* 2009) further reinforces the compelling nature of these stars for planet searches, and the high frequency of such habitable Super-Earths orbiting M dwarfs (∼ 40%; Bonfils *et al.* 2013) encourages us to search for such planets more intensively.

To carry out such planet searches around lower mass stars efficiently, a high-resolution near-infrared (nIR) spectroscopy is inevitable because the peak of flux distribution of late-M dwarfs appear in infrared wavelength regions and they are very faint in the visual. The success of nIR RV measurements, however, has been limited at the moment due to the absence of suitable instruments and the lack of a suitable spectral fiducial. While precise wavelength calibration using iodine absorption cells (Butler *et al.* 1996) or Th-Ar simultaneous reference techniques (Baranne *et al.* 1996) have made great success in achieving RV precision down to ∼1 m s^{-1} for optical wavelength region, such techniques have not been well established yet for nIR. Early works in nIR RV measurements used telluric lines as a wavelength reference and demonstrated a precision of 20–300 m s^{-1} (e.g., Blake *et al.* 2007; Prato *et al.* 2008; Blake *et al.* 2010; Seifahrt *et al.* 2008). Recently, Bean *et al.* (2010) first reached a precision better than 10 m s^{-1} using CRIRES. They used an ammonia gas absorption cell as a wavelength reference in K band and demonstrated that precisions of ∼5 m s^{-1} are obtainable over 6 months, and precisions better than ∼3 m s^{-1} can be obtained over timescales up to a week. They also installed a copy of the ammonia cell to IRCS spectrograph on the Subaru telescope and achieved a precision of about 30 m s^{-1} (Usuda *et al.* private communication). Although the precision of 5 m s^{-1} currently achieved is high enough to detect Neptune-mass planets around M–L dwarfs, state-of-the-art instruments which can achieve a precision of 1 m s^{-1} is highly required for detections of Super-Earths and Earth-like planets in the habitable zone.

IRD (InfraRed Doppler instrument; Tamura *et al.* 2012) is a new nIR high-dispersion spectrograph for precise RV measurements which will be attached to the Subaru 8.2-m telescope. It has a relatively compact (∼ 1 m) size with a new echelle-grating and Volume-Phase Holographic gratings covering 1–2 μm wavelength region, combined with a laser frequency comb using optical pulse synthesizer for precise wavelength reference. Stellar light and comb beams are fed into the spectrograph via optical fibers placed at the Nasmyth platform or a similar stable place of the Subaru telescope. The RV measurement precision is expected to be about 1 m s^{-1}. Utilizing the large aperture and high image quality of the Subaru telescope, IRD plans to conduct a large scale systematic RV surveys for hundreds of nearby middle-to-late M dwarfs aiming to detect planets down to Earth-mass in their habitable zone. Systematic observational and theoretical studies of M dwarfs and their planets for the IRD science are also ongoing. Details of the instrument and observing strategy are described by Tamura *et al.* (2012) and also by Omiya *et al.* in this volume.

4. Summary

In this paper research activities in East Asia for RV exoplanet searches were presented. The East-Asian Planet Search Network has been searching for planets around hundreds of evolved intermediate-mass stars and discovered about 30 planets and brown dwarfs so far. The Subaru/IRD is now under development to search for habitable planets around M dwarfs. These activities will contribute to the general understanding of exoplanets.

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References

Ando, H., Tsuboi, Y., Kambe, E., & Sato, B. 2010, *PASJ*, 62, 1117
Baranne, A., *et al.* 1996, *A&AS*, 119, 1117
Batalha, N. M., *et al.* 2013, *ApJS*, 204, article.id 24
Bean. J. L., Seifahrt, A., Hartman, H., Nilsson, H., Wiedemann, G., Reiners, A., Dreizler, S., & Henry, T. J. 2010, *ApJ*, 713, 410
Blake, C. H., Charbonneau, D., White, R. J., Marley, M. S., & Saumon, D. 2007, *ApJ*, 666, 1198
Blake, C. H., Charbonneau, D., & White, R. J. 2010, *ApJ*, 723, 684
Bonfils, X., *et al.* 2013, *A&A*, 549, A109
Borucki, W. J., *et al.* 2012, *ApJ*, 745, 120
Bowler, B. P., *et al.* 2010, *ApJ*, 710, 1365
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & and Vogt, S. S. 1996, *PASP*, 108, 500
Covey, K. R., *et al.* 2008, *AJ*, 136, 1778
Han, I., *et al.* 2010, *A&A*, 509, 24
Howard, A. W., *et al.* 2011, *Science*, 330, 653
Howard, A. W., *et al.* 2012, *ApJS*, 201, 15
Izumiura, H. 2005, *JKAS*, 38, 81
Johnson, J. A., *et al.* 2007a, *ApJ*, 665, 785
Johnson, J. A., *et al.* 2007b, *ApJ*, 670, 833
Johnson, J. A., Aller, K. M., Howard, A. W., & Crepp, J. R. *PASP*, 122, 905
Kambe, E., *et al.* *PASJ*, 60, 45
Lee, B.-C., Han, I., & Park, M.-G. 2013, *A&A*, 549, A2
Liu, Y.-J., *et al.* 2008, *ApJ*, 672, 553
Lovis, C. & Mayor, M. 2007, *A&A*, 472, 657
Mayor, M., *et al.* 2009, *A&A*, 507, 487

Mayor, M., *et al.* 2011, *A&A* submitted (arXiv: 1109.2497)

Niedzielski, A., Gozdziewski, K., Wolszczan, A., Konacki, M., Nowak, G., & Zielinski, P. 2009, *ApJ*, 693, 276

Omiya, M., *et al.*, 2009, *PASJ*, 61, 825

Omiya, M., *et al.*, 2012, *PASJ*, 64, 34

Pasquini, L., *et al.* 2007, *A&A*, 473, 979

Pepe, F., *et al.* 2011, *A&A*, 534, 58

Prato, L., Huerta, M., Johns-Krull, C. M., Mahmud, N., Jaffe, D. T., & Hartigan, P. 2008, *ApJ*, 687, 103

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

Sato, B., *et al.* 2008, *PASJ*, 60, 539

Sato, B., *et al.* 2010, *PASJ*, 62, 1063

Sato *et al.* 2012, *PASJ*, 64, Article No. 135

Seifahrt, A. & Käufl, H. U. 2008, *A&A*, 491, 929

Selsis, F., Kasting, J. F., Levrard, B., Paillet, J., Ribas, I., & and Delfosse, X. 2007, *A&A*, 476, 1373

Takeda, Y., Sato, B., & Murata, D., 2008, *PASJ*, 60, 781

Tamura, M., *et al.* 2012, *SPIE*, 8446

Udry, S. & Santos, N. C. 2007, *ARAA*, 45, 397

Wang, L., *et al.* 2012, *RAA*, 12, 84

Yilmaz, M., Selam, S. O., Sato, B., Izumiura, H., Bikmaev, I., Ando, H., Kambe, E., & Keskin, V. 2013, *New Astronomy*, 20, 24