Exoplanets Revealed by High-Precision Infrared Doppler Technique Using IRD: Large Exploration for Planets around Cool M-type Stars Begins

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Planets outside the Solar system, so-called exoplanets, are promising as a new window for astrobiology. Among those, planets orbiting cool M-type stars (main-sequence stars with effective temperatures less than about 3000 K) have the great potential to push forward astrobiological studies on exoplanets. The habitable zone (HZ) is the zone where liquid water is sustainable on the surfaces of planets. It is expected that the HZs around cooler stars come closer to the parent stars (Kopparapu et al. 2013, ApJ 765, 131). In addition, the recent exoplanet observations performed by the *Kepler* space telescope have revealed that the occurrence rate of small exoplanets similar to Earth increases as the effective temperatures of stars decrease (e.g., Mulders et al. 2015, ApJ 798, 112). Furthermore, the Doppler technique, one of primary methods for exoplanet observations, can more easily find a planet with the orbit closer to its parent star. Accordingly, targeting cool M-type stars provides a significant advantage in the observations of rocky planets in HZs based on the Doppler technique. Also, the snow line around a cool M-type star is close to the star; this is intriguing in terms of the planet formation process.
Nevertheless, the exoplanet observations for cool M-type stars have not been advanced compared with those for hotter stars, due to their faintness. In particular, the low brightness of a cool M-type star at optical wavelengths makes it problematic to observe its planet based on visible light, which has been mostly used in exoplanet observations. We have therefore developed the InfraRed Doppler (IRD) instrument, which is a high-dispersion spectrograph to enable the exoplanet observations using the high-precision Doppler technique at near-infrared (Kotani et al. 2018, Proc. of the SPIE 10702, 1070211). Near-infrared light is suited for observing cool M-type stars, since their peak flux is located in a near-infrared region. One of bottlenecks to achieve high-precision measurements using the near-infrared Doppler technique is the lack of a reference source that enables us to correctly calibrate a measurement fluctuation caused by the instability of an observation instrument. We use a laser frequency comb (LFC) generated by the system that has been newly developed for IRD as a reference source to calibrate IRD measurements. An LFC spectrum has a number of emission lines with fine sampling intervals and is observed simultaneously with a stellar spectrum, so it works as a correct wavelength calibrator for the stellar spectrum. After our laboratory performance verifications of IRD with its LFC system (Kuzuhara et al. 2018, Proc. of the SPIE 10702, 1070260), the IRD operation started on the Subaru Telescope, whose large primary mirror enables high-sensitivity observations even for cool M-type stars. The use of IRD with the Subaru Telescope significantly helps the discoveries and characterizations of exoplanets around cool M-type stars.
We have planned a large survey for planets around cool M-type stars with IRD on the Subaru Telescope, which actually begins on February, 2019. In this survey, we monitor 60 M-type stars over 175 nights

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allocated for 5 years. Our pre-survey simulation prospects more than 60 planet detections; those discoveries include a few dozen Earth-like planets, among which some are expected to locate within HZs. Thus, the IRD survey provides important contributions on improving our current understanding of planet formation models for low-mass stars like cool M-type stars, as well as the provisions of samples for exoplanet characterizations using the future large telescopes such as TMT. Here, we report the result of our ongoing on-sky tests to evaluate the IRD performances such as its measurement precision and stability. Furthermore, we explain the above large program in detail: our science goals, and the target selection and observation strategy for the goals are provided.

Keywords: Exoplanet, Doppler technique, Habitable Zone, IRD, planet formation, M-type star

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