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Search for Close-in Planets around Evolved Stars with Phase-curve variations and Radial Velocity Measurements

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Abstract. Tidal interactions are a key process to understand the evolution history of close-in exoplanets. But tidals still have a large uncertainty in their prediction for the damping timescales of stellar obliquity and semi-major axis. We have worked on a search for transiting giant planets around evolved stars, for which few close-in planets were discovered. It has been reported that evolved stars lack close-in planets, which is often attributed to the tidal evolution and/or engulfment of close-in planets by the hosts. Meanwhile, *Kepler* has detected a certain fraction of transiting planet candidates around evolved stars. Confirming the planetary nature for these candidates is especially important since the comparison between the occurrence rates of close-in planets around main sequence stars and evolved stars provides a unique opportunity to discuss the final stage of close-in planets. With the aim of confirming KOI planet candidates around evolved stars, we measured precision radial velocities (RVs) for evolved stars with transiting planet candidates using Subaru/HDS. We also developed a new code which simultaneously models and fits the observed RVs and phase-curve variations in the Kepler data (e.g., transits, stellar ellipsoidal variations, and planet emission/reflected light). As a result of applying the global fit to KOI giants/subgiants, we confirmed two giant planets around evolved stars (Kepler-91 and KOI-1894), as well as revealed that KOI-977 is more likely a false positive.

Keywords. planets and satellites: individual (KOI-977, KOI-1894, KOI-2133)

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1. Introduction

It has been reported that evolved stars lack close-in planets, which is often attributed to the tidal evolution and/or engulfment of close-in planets by the hosts. In the past year, we have worked on a search for giant planets around evolved stars, for which few close-in planets were discovered. We resort to both radial velocity (RV) measurements and analysis of "phase-curve variations" for planetary candidates detected by *Kepler*. Phase-curve variations are comprised of Doppler boosting, ellipsoidal variations, and reflected/emission light from the companion. From a precise phase-folded light-curve, we can extract the system parameters such as companion's mass and scaled semi-major axis, etc. Among the three effects above, ellipsoidal variation is particularly important for close-in planets around evolved stars, since its amplitude is approximately proportional to the cube of stellar radius. Combining the analysis of phase-curves (including transits) with an RV measurement would enable a more precise determination of system parameters. We apply this technique to three KOI (Kepler Object of Interest) systems below.

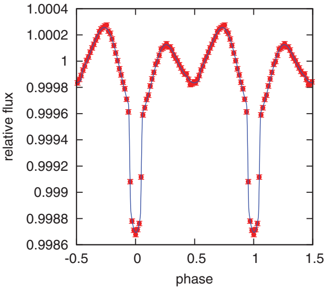

Figure 1. Phase-curve for KOI-977

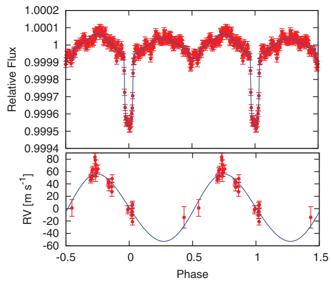

Figure 2. Phase-curve for Kepler-91

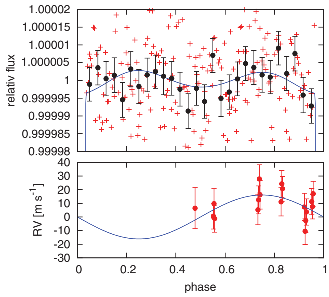

Figure 3. Phase-curve for KOI-1894

2. Analyses and Results

KOI-977: False Positive. We first focused on KOI-977, which is reported to be a red giant in the Kepler Input Catalog (KIC), with a close-in (P = 1.35 days) giant planet candidate. In order to confirm the planetary nature of KOI-977.01, we performed 1) RV measurements, 3) asteroseismic analysis, and 4) phase-curve analysis of Kepler data. Consequently, though the folded light-curve exhibits a clear pattern of phase-curve variations, our stellar analyses by spectroscopy and asteroseismology suggest that the estimated radius is too large for a star with a close-in planet; the estimated semi-major axis of the planet candidate KOI-977.01 is $\sim$ 0.027 AU, which is smaller than the stellar radius ($R_\star \sim$ 0.093 AU). Combining this fact with the small RV variation revealed by the Subaru/HDS observation, KOI-977.01 is very likely a false positive, meaning that the transit-like signal is caused by an eclipsing binary, which is not identical to the red giant for which we measured stellar radius and RVs. On the assumption that KOI-977 is comprised of a red giant and an eclipsing binary, we searched for a solution to the observed phase-curve. Figure 1 shows the observed phase-curve (red) and its best-fit model (blue) by our MCMC fit. The resulting mass and radius ratios of the eclipsing binary range between $0.11 < M_1/M_2 < 0.28$ and $0.13 < R_1/R_2 < 0.17$, respectively. These values correspond to those of an F star and an early M star (Hirano *et al.* 2015).

Kepler-91 and KOI-1894: Real Planets. Two other systems were targeted by our search for giant planets around evolved stars: Kepler-91 (KOI-2133) and KOI-1894 (Kepler-91b was reported to be a real planet by Lillo-box *et al.* 2013 before our publication). These two stars have similar properties (e.g., $R_\star = 6.3R_\odot$ for Kepler-91 and $R_\star = 8.6R_\odot$ for KOI-1894) and similar planetary candidates (jovian planets with P = 6.2 days and P = 5.3 days, respectively). In order to gain the system parameters as accurately as possible, we combined the RV data by Subaru/HDS and Kepler public light-curve and performed a global analysis. The results of the fits confirmed the planetary nature for both candidates; The best-fit models as plotted in Figures 2 and 3 suggest that Kepler-91b is a sub-Jupiter mass planet ($M_p = 0.64 \pm 0.05 M_J$) while KOI-1894b is more likely a super-Neptune planet ($M_p = 0.14 \pm 0.08 M_J$) (Sato *et al.* 2015).

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