A Close-in Planet Orbiting Giant Star HD 167768

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Abstract

We report the detection of a giant planet orbiting a G-type giant star HD 167768 from radial velocity measurements using HIgh Dispersion Echelle Spectrograph (HIDES) at Okayama Astrophysical Observatory (OAO). HD 167768 has a mass of $1.08_{-0.12}^{+0.14} M_{\odot}$, a radius of $9.70_{-0.25}^{+0.25} R_{\odot}$, a metallicity of $[\text{Fe/H}] = -0.67_{-0.08}^{+0.09}$, and a surface gravity of $\log g = 2.50_{-0.06}^{+0.06}$. The planet orbiting the star is a warm Jupiter, having a period of $20.65_{-0.0032}^{+0.0032}$ d, a minimum mass of $0.85_{-0.11}^{+0.12} M_J$, and an orbital semimajor axis of $0.15_{-0.0065}^{+0.0058}$ au. The planet has one of the shortest orbital periods among those ever found around deeply evolved stars ($\log g < 3.5$) using radial velocity methods. The equilibrium temperature of the planet is $1874$ K, as high as a hot Jupiter. The radial velocities show two additional regular variations at 41 d and 95 d, suggesting the possibility of outer companions in the system. Follow-up monitoring will enable validation of the periodicity. We also calculated the orbital evolution of HD 167768 b and found that the planet will be engulfed within 0.15 Gyr.

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1 Introduction

Planets around evolved stars have been widely surveyed over the last 20 years, and over 150 planets have been discovered around evolved stars \((\log g < 3.5)^1\) However, the lack of close-in planets around giant stars is well-known in the planet population study. Theoretically, radial velocity (RV) measurements should be more capable of discovering these close-in planets rather than wide-orbit ones. However, current surveys reveal that close-in \((a < 0.6 \text{ au})\) planets are seldom found around evolved stars (e.g. Johnson et al. 2007; Lillo-Box et al. 2016; Medina et al. 2018; Teng et al. 2022), while most of the planets survive at distant places to their host stars.

Planet population synthesis suggests the lack of close-in planets could be caused by a scaling of the proto-planetary disk mass with the mass of the central star (Alibert et al. 2011), but the scaling would be the case only if associated with a decrease in the mean disk lifetime for stars more massive than \(1.5 \, M_\odot\). Theoretical studies in stellar evolution suggest the lack of close-in planets could be also attributed to the expansion of central stars ending with planet engulfment (e.g., Villaver & Livio 2009; Kunitomo et al. 2011; Villaver et al. 2014). This scenario would be at least the case for low-mass giant stars \((M \lesssim 1.5 \, M_\odot)\), where a large number of short-period planets have been detected around their progenitors, that is, main-sequence stars. Furthermore, hot Jupiters may be also destroyed by tidal interactions during the main sequence lifetimes of their host stars (Hamers & Schlaufman 2019).

To date, several close-in planets have been confirmed around evolved stars, and five of them were detected to orbit giant stars with \(\log g < 3.5\) and \(R > 5 \, R_\odot\): Kepler-91 is detected by transiting, having a hot Jupiter with a semimajor-axis of 0.0731 au and orbital period of 24658 d. TYC 3667-1280-1 (Niedzielski et al. 2016) and 24 Boo (Takarada et al. 2018) host warm Jupiters with semimajor-axes of \(\sim 0.2\) au and orbital periods of \(\sim 30\) d. 8 UMi (Lee et al. 2015) and HIP 67851 (Jones et al. 2015) host planets with semimajor-axes of \(\sim 0.2\) au and orbital periods of \(\sim 90\) d. In addition, there are another 13 planets orbiting evolved stars of \(\log g < 3.5\) and \(R > 3 \, R_\odot\) with periods shorter than 100 days, e.g. Kepler-56 b and c (Huber et al. 2013), Kepler-432 b (Quinn et al. 2015), K2-97 b (Grunblatt et al. 2016), K2-132 b (Grunblatt et al. 2017), TOI-2269 b (Grunblatt et al. 2022), HD 33142 d (Trifonov et al. 2022).

In addition, based on the latest research on the occurrence rate of planets around evolved stars with radii of \(\sim 3 - 8 \, R_\odot\) given by Grunblatt et al. (2019) and Pereira (2022), they illustrated that the occurrence of hot Jupiters around these stars is in agreement with the hot Jupiter occurrence rate determined for main sequence stars. Thus it can be expected that the lack of planets found in evolved stars with large radii \((R > 5 \, R_\odot)\) may be due simply to observational bias rather than an actual deficit of planets.

In this paper, we present the discovery of a giant planet orbiting a deeply evolved solar-mass G-type giant star (HD 167768: \(\log g = 2.50\)) on a close-in orbit \((a = 0.1512\) au) from radial velocity (RV) measurements at Okayama Astrophysical Observatory (OAO). In Section 2 and 3 we present stellar properties and observations. In Section 4 and 5 we solve the orbit and analyze the line profile and chromospheric activity. Finally, in Section 6, we discuss the results and summarize this work.

| Parameter | Values | Source |
|-----------|--------|--------|
| \(\pi\) (mas) | 9.2289 | Gaia EDR3 |
| \(V\) | 6.00 | Hipparcos |
| \(B - V\) | 0.89 | Hipparcos |
| Spec. type | G8 III | Houk & Swift (1999) |
| \(T_{\text{eff}, \text{sp}}\) (K) | 4830 | Spectroscopy* |
| \([\text{Fe}/H]_{\text{sp}}\) (dex) | -0.75 | Spectroscopy* |
| \(\log g_{\text{sp}}\) (cgs) | 2.49 | Spectroscopy* |
| \(T_{\text{eff}}\) (K) | 4851±45 | isochrones* |
| \([\text{Fe}/H]\) (dex) | -0.67±0.09 | isochrones* |
| \(\log g\) (cgs) | 2.50±0.06 | isochrones* |
| \(L_\star\) (\(L_\odot\)) | 46.7±2.0 | isochrones* |
| \(M_\star\) (\(M_\odot\)) | 1.08±0.14 | isochrones* |
| \(R_\star\) (\(R_\odot\)) | 9.70±0.25 | isochrones* |
| Age (Gyr) | 5.31±2.47 | isochrones* |

* Determined this work.

1 NASA Exoplanet Archive https://exoplanetarchive.ipac.caltech.edu (Akeson et al. 2013)
log L/L⊙ 0.6 0.8 1.0 1.2 1.6 2.2
log (T eff ) 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2

Fig. 1. HR diagram for HD 167768. The star is marked by a open diamond. Evolution tracks of stars having masses between 0.8 and 1.6 M⊙ with HD 167768 metallicity ([Fe/H] = −0.67) are shown in solid lines using different colors in the main figure. (A colored version of this figure is available in the online journal.)

Fig. 2. Spectra in the region of Ca II H lines of HD 167768 with an active star HD 120048 as a comparison. Vertical offsets are added to each normalized spectrum for clarity, and a shaded area is used to mark the core region. A more detailed introduction to the HIDES fiber-link mode upgrade and its performance will be given in a forthcoming paper.

The best fit were derived from the posterior of a nested sampling with PyMultiNest package. Consequently, we obtained L∗ = 46.7 +2.0 −2.6 L⊙, R∗ = 9.70 +0.25 −0.35 R⊙, and M∗ = 1.08 +0.14 −0.05 M⊙. Besides, we estimated a maximum rotational period of P rot = sin i = 111 d from the projected rotational velocity of star v sin i = 4.44 km s−1 (Takeda, et al. 2008) and the star’s radius. A complete listing of stellar properties is given in Table 1, and a plot in the HR diagram is given in Figure 1.

HD 167768 is stable in Hipparcos V-band photometry with a level of σ HIP = 0.007 mag (ESA: van Leeuwen 2007) among three years, as well as All Sky Automated Survey (ASAS-3) V-band photometry with a level of σ ASAS = 0.03 mag (Pojmanski 1997) among 7.3 years. This star is also chromospherically inactive with no significant emission in the core of the Ca II H lines. We show its spectrum in Figure 2 together with another spectrum of a chromospherically active G-type giant star HD 120048.

3 Observations and RV measurements
In this work, all the spectra of HD 167768 were obtained from the 1.88-m reflector with High Dispersion Echelle Spectrograph (HIDES: Izumiura 1999) at Okayama Astrophysical Observatory. Its first spectrum was taken in 2004 March under the Okayama Planet Search Program (Sato et al. 2005), an extensive planet survey focusing on RV measurements to late-G (including early-K) giant stars. During the 18-year observations, the instrument had been upgraded several times. In December 2007, the CCD of HIDES was upgraded from the single one to a mosaic of three, which widened the wavelength region from 5000-6100 Å to 3700-7500 Å, and enabled us to simultaneously measure the level of stellar activities (e.g., Ca II H lines) and line profiles as well as radial velocities. In 2010, a new high-efficiency fiber-link system with its own iodine cell was installed on the HIDES, which greatly enhanced the overall throughput (Kambe et al. 2013). In 2018, another upgrade was carried out to enhance the performance of the fiber-link system with a newly designed optical path and stabilizing platform2. In this upgrade, the slit mode elements were entirely removed from the HIDES optical path. Hereafter, we name the observation taken by conventional slit mode, fiber mode pre-upgrade in 2018, and fiber-mode post-upgrade in 2018 as HIDES-S, HIDES-F1, and HIDES-F2, respectively.

In the case of HIDES-S observations, the slit width was set to 200 μm (0.76") corresponding to the resolution R = λ/Δλ ~ 67000 by about 3.3-pixel sampling. The
4 Orbit fitting and planetary parameters

First, we performed a Generalized Lomb-Scargle periodogram (hereafter GLS: Zechmeister & Kürster 2009, Figure 3) to search for periodicity in the time series and calculated False Alarm Probability (FAP) to assess the significance of the periodicity. We considered a peak in GLS with FAP significantly lower than 0.1% as a credible signal for regular variation.

The Keplerian orbital fit was finished similarly to our previous works (Teng et al. 2022). We generated Keplerian model and priors with RadVel package. The fitted Keplerian orbital elements includes orbital period $P$, RV semi-amplitude $K$, the combination of eccentricity $e$ and argument of periastron $\omega$, $\sqrt{e} \cos \omega$ and $\sqrt{e} \sin \omega$, and time of inferior conjunction $T_C$. The extra jitter $s$ and RV offset to zero point $\gamma$ were also set as free parameters, and the pariastron passage $T_p$ was derived from inferior conjunction $T_C$.

The best-fit Keplerian orbit and its uncertainties were derived by the maximum a posteriori (MAP) method from Markov Chain Monte Carlo (MCMC) sampling with emcee package. Model selection adopted reduced Chi-square $\chi^2_{red}$ and Bayesian Information Criteria (BIC: Schwarz 1978).

For HD 167768 RVs, we could find a strong signal at 20 d, indicating a regular variation in the time series. We then fitted a single Keplerian to the data in the way above. Consequently, we obtained orbital parameters of $P = 20.6532^{+0.0032}_{-0.0032}$ d, $K = 61.06^{+6.74}_{-6.96}$ m s$^{-1}$, and $e = 0.149^{+0.092}_{-0.097}$. Adopting a stellar mass of $1.08 M_\odot$, we obtained a minimum mass of $M_p \sin i = 0.85^{+0.12}_{-0.11} M_J$ and a semimajor axis of $a = 0.1512^{+0.0058}_{-0.0063}$ au for the planet. The best-fit single Keplerian model has a decreased BIC value of 60 compared to the No-planet model, suggesting the significance of the RV variation. A detailed parameter listing is given in Table 2, and the phase-folded orbit is shown in Figure 4.

The residuals to single Keplerian fit has rms of 40.25 m s$^{-1}$, which is significant larger than the esti-
Table 2. Orbital parameters

| Parameters | Best-fit | Prior       | Parameters | Best-fit | Prior       |
|------------|----------|-------------|------------|----------|-------------|
| $P$ (d)    | 20.6532+0.00349 | Jeffery’s (1,5000) | $s_0$ (m s$^{-1}$) | 42.70+3.71 | Mod-Jeffery’s (1.01(1),100) |
| $K$ (m s$^{-1}$) | 61.066+6.74 | Mod-Jeffery’s (1.01(1),1000) | $s_{f1}$ (m s$^{-1}$) | 45.52+6.12 | Mod-Jeffery’s (1.01(1),100) |
| $\sqrt{\gamma} \cos \omega$ | 0.1841+0.0339 | Uniform (−1,1) | $s_{f2}$ (m s$^{-1}$) | 33.36+6.16 | Mod-Jeffery’s (1.01(1),100) |
| $\sqrt{\gamma} \sin \omega$ | 0.30636+0.0374 | Uniform (−1,1) | $\gamma_0$ (m s$^{-1}$) | 1.59+7.73 | Uniform (−500,500) |
| $T_c$ (BJD−2450000) | 4595.44+0.73 | Uniform (3078,9731) | $\gamma_{f1}$ (m s$^{-1}$) | −9.55+7.91 | Uniform (−500,500) |
| $\epsilon$ | 0.1497+0.101 | (derived) | $\gamma_{f2}$ (m s$^{-1}$) | 7.15+7.09 | Uniform (−500,500) |
| $\omega$ (rad) | 1.0257+0.065 | (derived) | $\chi^2_{red}$ | 1.010 | (derived) |
| $T_p$ (BJD−2450000) | 4594.07+3.10 | (derived) | BIC | 1091.7 | (derived) |
| $M_p \sin i$ (M$_J$) | 0.85+0.12 | (derived) |                  |        |             |
| $a$ (au) | 0.1512+0.0058 | (derived) |                  |        |             |

The subscript “s”, “f1”, and “f2” refer to HIDES-S, -F1, and -F2 data respectively. Modified Jeffery’s prior has (min (knee value), max) (mod-Jeffery’s (1.01(1),1000)).

Fig. 4. Phase folded best-fit orbital solution of HD 167768. Upper panel: The best-fit orbital solution from the MCMC fitting. The black solid line shows the best-fit single Keplerian curve. The colored dots with errorbars are observed RVs in one orbital phase with fitted RV offsets shifted between instruments and with fitted jitters quadratically added to the observational errorbars. The non-colored dots are in extended half phases. Lower panel: The residuals to the best fit in the upper panel. In both two subplots, the symbols are the same. HIDES-S data are shown in light red circles, HIDES-F1 data are shown in light blue triangles, and HIDES-F2 data are shown in green squares. (A colored version of this figure is available in the online journal, and a complete RV data listing will be available online as supplementary after the publication.)

Fig. 5. Phase folded best-fit orbital solution of the possible extra companions in HD 167768 system. The symbols are the same as those in Figure 4. (A colored version of this figure is available in the online journal, and a complete RV data listing will be available online as supplementary after the publication.)

The corrected $p$-mode oscillation jitter of $10.1$ m s$^{-1}$ (Kjeldsen & Bedding 1995) or $20.4$ m s$^{-1}$ (Kjeldsen & Bedding 2011). In the periodogram of the residuals, there are two additional signals at $41$ d and $95$ d with FAP slightly lower than $0.1\%$, suggesting possible extra companions in the system. Keplerian fits yielded semi-amplitudes of $\sim 40$ m s$^{-1}$ and $\sim 34$ m s$^{-1}$ for the periodicity, corresponding to two planets of $0.68M_J$ at $0.24$ au and $0.80M_J$ at $0.42$ au, respectively (Figure 5). The rms of three-Keplerian is reduced to $\sim 26$ m s$^{-1}$, and BIC values is reduced to 1044, but the goodness-of-fit of $\chi^2_{red} = 1.056$ has larger deviation to unity compared to the single Keplerian result. Thus, continuous monitoring will enable us to validate the periodicity.

5 Line profile and chromospheric activity

We also calculated the deformation spectral line profiles and the flux of the chromospheric Ca II H line cores because line profile deformation and stellar chromospheric activity can both result in RV variations and mimic planetary signals (Queloz et al. 2001).

We follow the methodology in Takarada et al. (2018) and Teng et al. (2022). We use Bisector inverse span (BIS: Dall et al. 2006) as an indicator of line profile asymmetry. The BIS was defined as the velocity offset between the upper region and lower region in the cross-correlation function (CCF; Baranne et al. 1996; Pepe et al. 2002). Since different instruments show different instrumental profiles, we define the mean removed BIS (BIS' = BIS − BIS) to suppress the difference between instruments. The BIS calculations were based on the iodine-free spectra in the range of 4000–5000 Å. We also applied the Ca II H index ($S_H$; defined in Sato et al. 2013) to quantify the strength of chromospheric activity (Duncan et al. 1991). A clear cor-
relation between RV and $S_H$ can be detected (e.g., HD 120048 in Figure 9 in Sato et al. 2013) for a chromospheric active star having RV variate with $S_H$ simultaneously.

Illustrated in Figure 6, the BIS of HIDES-S, -F1, and -F2 have almost the same level of line dispersion, suggesting that stellar surface modulation should greatly affect the spectral line profile. However, BIS' has no correlation with RV ($r = 0.12$). Similarly, $S_H$ also has weak correlation with RV ($r = 0.24$). Furthermore, we calculated periodogram of BIS' and $S_H$ (Figure 3). Concerning the bundle of powerful high-frequency signals, the 20.7 d signal that appears in BIS' periodogram is not considered to be significant. The periodogram of $S_H$ as well as HIP and ASAS-3 light curves do not show any periodicity around the 20.7 d signal. Thus we conclude orbital motion is the source of 20.7 d RV variation.

6 Discussion and summary

We have reported the discovery of a giant planet orbiting the G type giant star HD 167768 (1.08$M_\odot$, 9.70$R_\odot$, and $g = 2.50$) on a close-in orbit ($P = 20.6532$ d, $a = 0.1512$ au) from radial velocity (RV) measurement at OAO. The planet, HD 167768 b, is known to have the shortest period and proximity to a central star having $R \gtrsim 10 R_\odot$.

Given the planet’s orbital parameters and star’s parameters, we can derive a transit probability of 35% and a maximum transit duration of 2.3 d (55 hr). The star is luminous and it results in a high planet’s equilibrium temperature of $T_{eq} = 1874$ K with assumed Bond albedo $A$ equal to 0:

$$T_{eq} = T_{eff} (1 - A)^{1/4} \sqrt{\frac{R^*}{2a}}.$$

The planet is the hottest Jupiter found by RV measurements, and it is comparable to the hottest giant planets ever detected. High irradiation for the expanding giant star could lead to an inflation of the warm Jupiter like HD 167768 (Lopez & Fortney 2016). Theoretically, a gas giant planet of 0.85$M_J$ orbiting a giant star of 1$M_\odot$ and 10$R_\odot$ with orbital period of 20 d could be inflated to approximately 2$R_J$ with interior heating efficiency of 0.5% (Figure 8 in Lopez & Fortney 2016). However, based on the actual measurement of the planet re-inflation efficiency ($K2$-97 b and K2-132 b; Grunblatt et al. 2016; Grunblatt et al. 2017), it is one order of magnitude lower than the theoretical prediction. Simply, if we assume a planet radius of 1.5$R_J$, we can expect a transit depth of about 0.02%, which is within the detectability of space telescopes. But unfortunately, this star is not included in the TESS observation plan by 2023 September 20th.

HD 167768 system is extremely compact concerning that the orbital separation at pericenter is only $a(1 - e) = 0.128$ au, that is 2.6$R_\ast$, and it is expected to have experienced tidal orbital decay (Villaver et al. 2014). The average $(a/R_\ast) \sim 3$ is also one of the smallest among the known planetary systems (Patra et al. 2020). Here, by assuming the reduced tidal quality factor $Q'_* \sim 10^6$ and equilibrium tide formulations in Patra et al. (2020), we can estimate that tidal inspiral timescale of HD 167768 b is approximately 0.5 Gyr.

The moderate eccentricity of HD 167768 b ($e = 0.149$) is indeed in line with the trend of detected close-in giant planets around evolved stars. Grunblatt et al. (2018) suggested that this trend results from the longer tidal circularization timescale than the tidal orbital decay timescale and thus the planets with moderate eccentricities are transient objects. However, we cannot estimate the orbit circularization timescale for two reasons. One is that the radius of the planet is unknown and (Patra et al. 2017), another one is that we are tentatively not sure if the system consists of outer companions (Section 4). Detailed analysis of the eccentricity evolution in future work is highly encouraged.

As the star is expected to be ascending the red giant branch (RGB; see Figure 1), the ultimate fate of the planet should be an engulfment. Sun et al. (2018) predicted the critical radius $a_{crit}(t)$ of main stars in binaries, where

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$^3$NASA Exoplanet Archive https://exoplanetarchive.ipac.caltech.edu (Akeson et al. 2013)

$^4$https://heasarc.gsfc.nasa.gov/cgi-bin/tess/webtess/vtv.py
The planet will be engulfed by the expanding star within 0.15 Gyr. Since the internal structure information is not available in the tidal model, we assumed that the star has a fully convective structure. We confirmed that this assumption does not have a significant impact on the result of orbital evolution.

Fig. 7. Evolutions of the planet’s semimajor axis (solid) and stellar radius (dashed). (A colored version of this figure is available in the online journal.)

Since the internal structure information is not available in the MIST model, we assumed that the star has a fully convective structure. We confirmed that this assumption does not have a significant impact on the result of orbital evolution.
lation: NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020) and astropy (Astropy Collaboration et al. 2013), isochrones (Morton 2015), PyMultiNest (Feroz & Hobson 2008; Feroz et al. 2009; Feroz et al. 2019), radvel (Fulton & Petigura 2017; Fulton, Petigura, Blunt, & Sinukoff 2018), and emcee (Foreman-Mackey, Hogg, Lang, & Goodman 2013).

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

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