A PAIR OF GIANT PLANETS AROUND THE EVOLVED INTERMEDIATE-MASS STAR HD 47366: MULTIPLE CIRCULAR ORBITS OR A MUTUALLY RETROGRADE CONFIGURATION

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ABSTRACT

We report the detection of a double planetary system around the evolved intermediate-mass star HD 47366 from precise radial-velocity measurements at the Okayama Astrophysical Observatory, Xinglong Station, and Australian Astronomical Observatory. The star is a K1 giant with a mass of 1.81 ± 0.13 MJ, a radius of 7.30 ± 0.33 RJ, and solar metallicity. The planetary system is composed of two giant planets with minimum masses of 1.75±0.20 MJ and 1.86±0.16 MJ, orbital periods of 363.3±2.5 days and 684.7±5.0 days, and eccentricities of 0.089±0.079 and 0.278±0.094, respectively, which are derived by a double Keplerian orbital fit to the radial-velocity data. The system adds to the population of multi-giant-planet systems with relatively small orbital separations, which are preferentially found around evolved intermediate-mass stars. Dynamical stability analysis for the system revealed, however, that the best-fit orbits are unstable in the case of a prograde configuration. The system could be stable if the planets were in 2:1 mean-motion resonance, but this is less likely, considering the observed period ratio and eccentricity. A present possible scenario for the system is that both of the planets have nearby circular orbits, namely the eccentricity of the outer planet is less than ~0.15, which is just within 1σ of the best-fit value, or the planets are in a mutually retrograde configuration with a mutual orbital inclination larger than 160°.

Key words: planetary systems – stars: individual (HD 47366) – techniques: radial velocities

1. INTRODUCTION

Evolved stars (giants and subgiants) have been extensively searched for the last 10 years, aiming to explore planets around more massive stars than the Sun and to investigate the orbital evolution of planetary systems during the post-main-sequence phase. Precise radial-velocity surveys have discovered about 120 substellar companions around such evolved stars12 so far, and they are now known to exhibit statistical properties that are not necessarily similar to those around solar-type stars. For example, 24 Sex (G5 IV; Johnson et al. 2011) and η Cet (K2 III; Trifonov et al. 2014) host double giant-planet systems probably in mean-motion resonances of 2:1, which suggests that these systems have experienced differential convergent

13 Evolved stars here include those with logarithmic surface gravity log g < 4.0. The list of the stars harboring substellar companions is from the NASA Exoplanet Archive.

14 NASA Exoplanet Archive.

15 One exception is the planetary system around the K2.5 V star HD 45364, which consists of two giant planets (m sin i = 0.187 MJ and m sin i = 0.658 MJ) in 3:2 resonance (Correia et al. 2009).
intermediate-mass stars at once, the two panels look nearly identical. The pairs discovered with ground-based, radial-velocity, and transit surveys. The pairs Cumulative number of planet pairs in multiple-planetary systems around the intermediate-mass giant HD 47366 (K0 III; Johnson et al. 2011) is listed in the Hipparcos Catalogue (ESA 1997) as a K1 III star, with a visual magnitude of $V = 6.11$ and a color index of $B - V = 0.994$. The Hipparcos parallax $\pi = 12.5 \pm 0.42$ mas (van Leeuwen 2007) corresponds to a distance of $80.0 \pm 2.7$ pc. The reddening $E(B - V) = 0.028$ was obtained from the Galactic dust map of Schlegel et al. (1998), with the correction given by Bonifacio et al. (2000) and a scaling factor of $1 - \exp(-|d \sin b|/h)$, where $d$ is the distance, $b$ is the Galactic latitude, and $h = 125$ pc is the scale height of the reddening layer. The absolute magnitude $M_V = 1.51$ was derived from the distance and the interstellar extinction $A_V = 3.1E(B - V)$. By adopting the broadband photometric color $B - V$ and the estimated metallicity with the empirical calibration relation of Alonso et al. (1999, 2001), we derived the bolometric correction $B.C. = -0.309$ and the effective temperature $T_{\text{eff}} = 4866 \pm 100$ K. We used a high signal-to-noise ratio $(S/N \sim 200)$, iodine-free spectrum taken with HRS to measure the equivalent widths (EWs) of $\sim 30$ Fe I lines, to derive the iron abundance [Fe/H]. The line lists as well as their oscillation strengths $(\log gf)$ were mainly taken from Hekker & Meléndez (2007), in which iron lines were carefully selected to avoid any blend by atomic or CN lines. The model atmosphere used in this work was interpolated from the line-blanketed, local thermodynamic equilibrium (LTE) ATLAS9-ODFNEW grid (Castelli & Kurucz 2004). The microturbulent velocity $v_t$ was obtained by minimizing the trend between the abundances of different Fe I lines and their reduced equivalent widths $(\log EWs/\lambda)$. The macroturbulent velocity was estimated with the empirical relations of $v_{\text{macrotur}}$ versus $T_{\text{eff}}$ given by Hekker & Meléndez (2007), and the projected rotational velocity $(v \sin i)$ was determined with the method of Kefel (1997). The stellar mass, surface gravity $(\log g)$, radius, and age were derived using a Bayesian approach with the Geneva database (Lejeune & Schaerer 2001), which includes the post-helium flash phases for stars with $M \geq 1.7 M_{\odot}$. First, we interpolated an extensive grid of evolutionary tracks, with $\Delta M = 0.05$ within $1.2 \leq M/M_{\odot} \leq 3.6$, $\Delta [\text{Fe/H}] = 0.02$ within $-0.4 \leq [\text{Fe/H}] \leq +0.3$, and 500 points in each track. Then, for each data point, we calculated the likelihood functions of $\log L$, $T_{\text{eff}}$ and [Fe/H] to match the observed values by assuming Gaussian errors. We adopted uniform prior probabilities of mass and [Fe/H]. It is noted that stars evolving more slowly have a higher probability of being observed. Without correcting this evolution effect, the resulting parameters would bias toward the rapid evolution phases. We therefore weighted the probability of each point along its evolutionary track by the normalized time-step $(a_{i+1,j} - a_{i,j})/(a_{n,j} - a_{i,j})$, where $a_{i,j}$ is the age of observations from the Australian Astronomical Observatory (Sato et al. 2013a). The planetary system is intriguing for several reasons: the best-fit Keplerian orbit is unstable, it is near but less likely in 2:1 mean-motion resonance, and could be stable if the orbits are nearly circular or in retrograde configuration.

The rest of the paper is organized as follows. The stellar properties are presented in Section 2 and the observations are described in Section 3. The orbital solution and results of dynamical stability analysis are presented in Sections 4 and 5, respectively. Section 6 is devoted to discussion and summary.

2. STELLAR PROPERTIES

HD 47366 (HIP 31674, BD–12 1566, HR 2437, TYC 5373-2001-1) is listed in the Hipparcos Catalogue (ESA 1997) as a K1 III star, with a visual magnitude of $V = 6.11$ and a color index of $B - V = 0.994$. The Hipparcos parallax $\pi = 12.5 \pm 0.42$ mas (van Leeuwen 2007) corresponds to a distance of $80.0 \pm 2.7$ pc. The reddening $E(B - V) = 0.028$ was obtained from the Galactic dust map of Schlegel et al. (1998), with the correction given by Bonifacio et al. (2000) and a scaling factor of $1 - \exp(-|d \sin b|/h)$, where $d$ is the distance, $b$ is the Galactic latitude, and $h = 125$ pc is the scale height of the reddening layer. The absolute magnitude $M_V = 1.51$ was derived from the distance and the interstellar extinction $A_V = 3.1E(B - V)$. By adopting the broadband photometric color $B - V$ and the estimated metallicity with the empirical calibration relation of Alonso et al. (1999, 2001), we derived the bolometric correction $B.C. = -0.309$ and the effective temperature $T_{\text{eff}} = 4866 \pm 100$ K. We used a high signal-to-noise ratio $(S/N \sim 200)$, iodine-free spectrum taken with HRS to measure the equivalent widths (EWs) of $\sim 30$ Fe I lines, to derive the iron abundance [Fe/H]. The line lists as well as their oscillation strengths $(\log gf)$ were mainly taken from Hekker & Meléndez (2007), in which iron lines were carefully selected to avoid any blend by atomic or CN lines. The model atmosphere used in this work was interpolated from the line-blanketed, local thermodynamic equilibrium (LTE) ATLAS9-ODFNEW grid (Castelli & Kurucz 2004). The microturbulent velocity $v_t$ was obtained by minimizing the trend between the abundances of different Fe I lines and their reduced equivalent widths $(\log EWs/\lambda)$. The macroturbulent velocity was estimated with the empirical relations of $v_{\text{macrotur}}$ versus $T_{\text{eff}}$ given by Hekker & Meléndez (2007), and the projected rotational velocity $(v \sin i)$ was determined with the method of Kefel (1997). The stellar mass, surface gravity $(\log g)$, radius, and age were derived using a Bayesian approach with the Geneva database (Lejeune & Schaerer 2001), which includes the post-helium flash phases for stars with $M \geq 1.7 M_{\odot}$. First, we interpolated an extensive grid of evolutionary tracks, with $\Delta M = 0.05$ within $1.2 \leq M/M_{\odot} \leq 3.6$, $\Delta [\text{Fe/H}] = 0.02$ within $-0.4 \leq [\text{Fe/H}] \leq +0.3$, and 500 points in each track. Then, for each data point, we calculated the likelihood functions of $\log L$, $T_{\text{eff}}$ and [Fe/H] to match the observed values by assuming Gaussian errors. We adopted uniform prior probabilities of mass and [Fe/H]. It is noted that stars evolving more slowly have a higher probability of being observed. Without correcting this evolution effect, the resulting parameters would bias toward the rapid evolution phases. We therefore weighted the probability of each point along its evolutionary track by the normalized time-step $(a_{i+1,j} - a_{i,j})/(a_{n,j} - a_{i,j})$, where $a_{i,j}$ is the age of
the \( i \)th interpolated point in the \( j \)th track, and \( n = 500 \) is the number of interpolated points in each track. Eventually, the probability distribution functions (PDFs) of the parameters yield \( M = 1.81 \pm 0.13 \, M_\odot \), \( R = 7.30 \pm 0.33 \, R_\odot \), \( \log g = 2.97 \pm 0.06 \), and age = 1.61 \pm 0.53 Gyr. The stellar mass is particularly important to derive the minimum masses of the orbiting planets detected with the Doppler technique. However, previous spectroscopic analyses gave discrepant results \( (1.87 \, M_\odot \) by Liu et al. 2010; 1.2 \, M_\odot \) by Mishenina et al. 2006) for HD 47366, which may be due to the different methods on finding \( T_\text{eff} \) and \( \log g \). Our determinations were based on a similar method to that of Liu et al. (2010), but used the Geneva evolutionary tracks, instead of the \( Y^2 \) model (Yi et al. 2003, which does not account for the evolutionary phases after the helium-core flash. We found that the probability that the star has passed through the RGB tip and in-core helium burning phase is \( \sim 88\% \). The stellar parameters of HD 47366 are listed in Table 1. In Figure 2, we plotted HD 47366 on the H-R diagram, together with the evolutionary tracks for stars with different masses and metal contents.

The star shows no significant emission in the core of Ca II HK lines, as shown in Figure 3, which suggests that the star is chromospherically inactive. We did not analyze flux variations of Ca II HK lines for the star because of the poor S/N of the core of the lines.

### 3. OBSERVATIONS

#### 3.1. OAO Observations

Observations of HD 47366 at OAO were made with the 1.88 m reflector and the High Dispersion Echelle Spectrograph (HIDES; Izumiura 1999) from 2006 December to 2014 April. We used both the conventional slit mode (HIDES-S) and the high-efficiency fiber-link mode (HIDES-F) of the spectrograph that became available in 2010 (Kambe et al. 2013). In the case of the HIDES-S, a slit width of the spectrograph was set to 200 \( \mu m \) (0\"76) corresponding to a spectral resolution \( R = \lambda/\Delta\lambda \) of 67,000 by about a 3.3-pixel sampling. In the case of HIDES-F, a width of the image sliced by an image slicer is 1\"05, corresponding to a spectral resolution of \( R = 55,000 \) by a 3.8-pixel sampling. Each observing mode uses its own iodine absorption cell for precise radial-velocity measurements (I\_2 cell; Kambe et al. 2002, 2013), which provide a fiducial wavelength reference in a wavelength range of 5000–5800 Å. We have obtained a total of 50 and 7 data points of HD 47366 using HIDES-S and HIDES-F mode, respectively. The reduction of echelle data (i.e., bias subtraction, flat-fielding, scattered-light
subtraction, and spectrum extraction) was performed using the IRAF\textsuperscript{16} software package in the standard way.

We performed a radial-velocity analysis following the method of Sato et al. (2002, 2012) and Butler et al. (1996), in which an I\textsubscript{2}-superposed spectrum is modeled as a product of a high-resolution I\textsubscript{2} and a stellar template spectrum convolved with a modeled point-spread function (PSF) of the spectrograph. We model the PSF using multiple Gaussian profiles (Valenti et al. 1995) and obtain the stellar spectrum by deconvolving a pure stellar spectrum with the spectrograph PSF estimated from an I\textsubscript{2}-superposed B-star spectrum. We obtained a typical measurement error in radial-velocity of about $4-5$ m s$^{-1}$ for the star, which was estimated from an ensemble of velocities from each of the $\sim$300 spectral chunks (each $\sim$3 Å long) in every exposure. We listed the derived radial velocities for OAO data in Table 2 together with the estimated uncertainties.

### 3.2. Xinglong Observations

Observations of HD 47366 at the Xinglong Station started in 2006 November using the 2.16 m reflector and the Coude Echelle Spectrograph (CES; Zhao & Li 2001). We used the blue-arm, middle focal length camera, and 1 K $\times$ 1 K CCD (pixel size of $24 \times 24$ $\mu$m$^2$; hereafter CES-O) of the spectrograph, which covered a wavelength range of 3900–7260 Å with a spectral resolution of 40,000 by 2-pixel sampling. Although a wide wavelength range was obtained with a single exposure, only a wave band of $\Delta \lambda \sim 470$ Å was available for radial-velocity measurements using an I\textsubscript{2} cell because of the small format of the CCD. Radial-velocity analysis for CES data was performed by the optimized method of Sato et al. (2002) for

![Figure 3. Spectra in the region of Ca II H lines. Stars with similar spectral types to HD 47366 in our sample are also shown. A vertical offset of about 0.4 is added to each spectrum.](image)

| JD−2450000 | Velocity (m s$^{-1}$) | Uncertainty (m s$^{-1}$) | Mode |
|------------|------------------------|--------------------------|------|
| 4093.18674 | 11.36                  | 4.59                     | HIDES-S |
| 4144.11514 | −19.66                 | 4.69                     | HIDES-S |
| 4172.01541 | −18.29                 | 3.85                     | HIDES-S |
| 4467.12999 | −4.46                  | 4.31                     | HIDES-S |
| 4553.97104 | −31.25                 | 4.14                     | HIDES-S |
| 4755.29094 | 32.92                  | 3.46                     | HIDES-S |
| 4796.25111 | 36.33                  | 4.17                     | HIDES-S |
| 4818.17076 | 19.49                  | 3.87                     | HIDES-S |
| 4823.11554 | 14.96                  | 4.17                     | HIDES-S |
| 4834.16358 | 12.38                  | 4.36                     | HIDES-S |
| 4856.08725 | −6.42                  | 3.92                     | HIDES-S |
| 4863.09739 | −6.67                  | 4.41                     | HIDES-S |
| 4864.05798 | −11.43                 | 3.60                     | HIDES-S |
| 4883.04016 | −7.18                  | 4.55                     | HIDES-S |
| 4923.93523 | −17.64                 | 3.73                     | HIDES-S |
| 5108.31507 | 40.77                  | 4.18                     | HIDES-S |
| 5131.32499 | 47.90                  | 3.57                     | HIDES-S |
| 5163.34864 | 39.99                  | 4.64                     | HIDES-S |
| 5182.16055 | 11.19                  | 4.10                     | HIDES-S |
| 5204.11564 | −7.29                  | 4.29                     | HIDES-S |
| 5232.99361 | −43.84                 | 3.62                     | HIDES-S |
| 5267.01163 | −60.09                 | 3.57                     | HIDES-S |
| 5294.93562 | −62.39                 | 3.54                     | HIDES-S |
| 5471.29879 | 24.76                  | 3.61                     | HIDES-S |
| 5502.23739 | 33.89                  | 4.15                     | HIDES-S |
| 5525.22640 | 33.98                  | 4.85                     | HIDES-S |
| 5545.21850 | 18.86                  | 3.73                     | HIDES-S |
| 5581.04001 | −12.92                 | 3.75                     | HIDES-S |
| 5611.01311 | −8.59                  | 4.13                     | HIDES-S |
| 5625.02350 | −13.62                 | 3.49                     | HIDES-S |
| 5656.93188 | −10.50                 | 3.74                     | HIDES-S |
| 5857.28485 | 33.84                  | 3.89                     | HIDES-S |
| 5877.25348 | 18.63                  | 5.42                     | HIDES-S |
| 5882.29797 | 12.23                  | 3.83                     | HIDES-S |
| 5922.13357 | −12.73                 | 3.88                     | HIDES-S |
| 5938.09758 | −34.44                 | 3.79                     | HIDES-S |
| 5976.03887 | −49.42                 | 4.57                     | HIDES-S |
| 6010.93116 | −64.77                 | 5.74                     | HIDES-S |
| 6032.96687 | −55.43                 | 4.48                     | HIDES-S |
| 6215.30762 | 27.47                  | 4.04                     | HIDES-S |
| 6235.27265 | 41.83                  | 3.68                     | HIDES-S |
| 6249.30138 | 27.36                  | 4.69                     | HIDES-S |
| 6284.08997 | −0.00                  | 4.69                     | HIDES-S |
| 6552.29701 | 42.87                  | 5.53                     | HIDES-S |
| 6577.28414 | 4.35                   | 4.84                     | HIDES-S |
| 6578.28739 | 14.21                  | 4.48                     | HIDES-S |
| 6578.30265 | 14.55                  | 4.27                     | HIDES-S |
| 6579.25810 | 12.00                  | 5.63                     | HIDES-S |
| 6618.19944 | 4.11                   | 3.91                     | HIDES-S |
| 6753.98409 | −63.39                 | 4.45                     | HIDES-S |
| 6609.21551 | 21.82                  | 4.04                     | HIDES-F |
| 6616.27916 | 33.33                  | 3.44                     | HIDES-F |
| 6664.09442 | −1.41                  | 4.02                     | HIDES-F |
| 6672.05938 | −16.16                 | 3.85                     | HIDES-F |
| 6697.15561 | −9.17                  | 4.70                     | HIDES-F |
| 6713.98088 | −17.94                 | 4.87                     | HIDES-F |
| 6727.00570 | −12.14                 | 3.47                     | HIDES-F |

\textsuperscript{16} IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation, USA.
CES (Liu et al. 2008). We took five data points for HD 47366 using CES-O from 2006 November to 2007 December whose radial-velocity uncertainties were better than 25 m s\(^{-1}\). In 2009 March, the old CCD was replaced by a new CCD having a smaller pixel size (2 K \(\times\) 2 K, 13 \(\times\) 13 \(\mu\)m\(^2\)), and it gave a better radial-velocity precision than before, though the wavelength coverage was unchanged (Wang et al. 2012). We made observations of HD 47366 using the new CCD (hereafter CES-N) from 2009 December to 2010 December, and collected a total of 26 data points with a radial-velocity precision of 12–25 m s\(^{-1}\) depending on weather conditions.

Since 2011 November, we have observed HD 47366 with the newly developed High Resolution Spectrograph (HRS) attached at the Cassegrain focus of the 2.16 m telescope. The fiber-fed spectrograph is the successor of the CES, giving a higher wavelength resolution and throughput. The single 4 K \(\times\) 4 K CCD provides a simultaneous wavelength coverage of 3700–9200 Å, and the slit width of 190 \(\mu\)m gives a wavelength resolution of \(R = 45,000\) with a 3.2-pixel sampling. An iodine cell is installed before the fiber entrance at the Cassegrain focus. We collected a total of 60 observations for the star from 2011 November to 2014 March. Radial-velocity analysis for the HRS data was performed by the same method as Sato et al. (2002, 2012), but optimized for HRS. The resulting measurement errors in radial velocity are ranging from 6 to 20 m s\(^{-1}\) depending on weather conditions. The derived radial velocities for Xinglong data are listed in Table 3 together with the estimated uncertainties.

### 3.3. AAT Observations

Since the inner planet has a period near one year, and HD 47366 is quite far south for OAO, we obtained confirmation observations from the 3.9-m Anglo-Australian Telescope (AAT). This multi-telescope approach was also critical for the confirmation of the 360-day planet HD 4732b (Sato et al. 2013a). The UCLES echelle spectrograph (Diego et al. 1990) delivers a resolving power of \(R \approx 45,000\) with the 1-arcsecond slit, and has been used for 16 years by the Anglo-Australian Planet Search (e.g., Butler et al. 2001; Tinney et al. 2001; Jones et al. 2010; Wittenmyer et al. 2012b, 2014). Calibration of the spectrograph point-spread function is achieved using an iodine absorption cell temperature-controlled at 60.0 \(\pm\) 0.1°C. The iodine cell superimposes a forest of narrow absorption lines from 5000 to 6200 Å, allowing for the simultaneous calibration of instrumental drifts as well as a precise wavelength reference (Valenti et al. 1995; Butler et al. 1996). The result is a precision Doppler velocity estimate for each epoch, along with an internal uncertainty estimate, which includes the effects of photon-counting uncertainties, residual errors in the spectrograph PSF model, and variation in the underlying spectrum between the iodine-free template and epoch spectra observed through the iodine cell. HD 47366 was observed at 13 epochs between 2013 March and 2014 April; the AAT velocities are given in Table 4.

### 4. ORBIT FITTING AND PLANETARY PARAMETERS

The collected radial-velocity data for HD 47366 obviously show a variation with a period near one year. Although the one-year periodicity and the relatively low declination of the star allowed us to cover only half of the cycle, we can clearly see the periodic variation of the velocity amplitude every year.

| JD | Velocity (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) | Mode |
|----|------------------------|--------------------------|------|
| 5878.34042 | 43.36 | 13.50 | HRS |
| 5878.36563 | 33.75 | 13.50 | HRS |
| 5878.38866 | 0.73 | 16.05 | HRS |
| 5878.41177 | 42.81 | 16.18 | HRS |
| 5879.29416 | 4.27 | 19.96 | HRS |
| 5905.20117 | 23.16 | 11.56 | HRS |
| 5905.22422 | 14.68 | 12.04 | HRS |
| 5905.24720 | 36.90 | 14.27 | HRS |
| 5905.27024 | 48.98 | 15.64 | HRS |
| 5907.26067 | 1.38 | 8.18 | HRS |
| 5907.28402 | 8.44 | 9.30 | HRS |
| 5907.30698 | 8.20 | 10.15 | HRS |
| 5907.32995 | 7.82 | 9.57 | HRS |
| 5936.13872 | 43.36 | 13.50 | HRS |
| 5936.16225 | 35.52 | 10.34 | HRS |
| 5936.18572 | 32.01 | 10.67 | HRS |
| 5936.20863 | 22.04 | 11.92 | HRS |
| 5959.11008 | 30.57 | 22.97 | HRS |
| 5959.13303 | 43.36 | 20.46 | HRS |
| 5959.15600 | 43.22 | 18.84 | HRS |
| 5959.17896 | 62.76 | 24.07 | HRS |
| 5960.01241 | 44.45 | 13.47 | HRS |
| 5960.11747 | 39.46 | 15.51 | HRS |
| 5966.04907 | 39.47 | 19.32 | HRS |
| 5966.07211 | 31.79 | 20.95 | HRS |
| 5966.09510 | 79.17 | 17.80 | HRS |
| 5966.11809 | 67.76 | 17.67 | HRS |
| 5997.97169 | 66.24 | 10.18 | HRS |
| 5997.99495 | 52.05 | 11.16 | HRS |
| 5998.01824 | 47.66 | 11.05 | HRS |
| 5998.04152 | 60.49 | 10.68 | HRS |
| 6199.33390 | 51.35 | 6.54 | HRS |
indicating the existence of a second period near two years. Thus we performed the least-squares orbital fitting by a double Keplerian model. The orbital parameters and the uncertainties were derived using the Bayesian Markov Chain Monte Carlo (MCMC) method (e.g., Ford 2005; Gregory 2005; Ford & Gregory 2007), following the analysis in Sato et al. (2013b).

Table 3 (Continued)

| JD−2450000 | Velocity (m s$^{-1}$) | Uncertainty (m s$^{-1}$) | Mode |
|-------------|-----------------------|--------------------------|------|
| 6199.35708  | 45.59                 | 7.80                     | HRS  |
| 6232.33343  | 54.89                 | 5.89                     | HRS  |
| 6232.35667  | 61.48                 | 6.12                     | HRS  |
| 6287.81912  | 30.60                 | 9.50                     | HRS  |
| 6287.20515  | 35.52                 | 10.34                    | HRS  |
| 6287.22838  | 32.06                 | 9.39                     | HRS  |
| 6287.25312  | 47.44                 | 11.03                    | HRS  |
| 6318.08350  | 31.16                 | 11.25                    | HRS  |
| 6318.10670  | 13.27                 | 11.99                    | HRS  |
| 6318.13045  | 21.01                 | 12.00                    | HRS  |
| 6318.15375  | 25.07                 | 11.17                    | HRS  |
| 6344.02830  | 11.76                 | 8.52                     | HRS  |
| 6344.05152  | 23.29                 | 9.47                     | HRS  |
| 6344.07471  | 22.34                 | 9.87                     | HRS  |
| 6583.31389  | 22.42                 | 10.63                    | HRS  |
| 6583.33707  | 35.59                 | 11.03                    | HRS  |
| 6583.36032  | 20.96                 | 11.67                    | HRS  |
| 6611.28853  | 18.21                 | 7.27                     | HRS  |
| 6611.31171  | 20.81                 | 8.39                     | HRS  |
| 6611.33507  | 7.72                  | 8.55                     | HRS  |
| 6645.18797  | −18.03                | 12.37                    | HRS  |
| 6645.21133  | 9.17                  | 12.68                    | HRS  |
| 6645.23463  | −12.05                | 15.41                    | HRS  |
| 6645.25792  | −22.92                | 16.31                    | HRS  |
| 6701.05113  | −50.92                | 11.31                    | HRS  |
| 6701.07444  | −55.62                | 15.95                    | HRS  |
| 6728.98753  | −39.22                | 16.13                    | HRS  |
| 6729.01088  | −50.79                | 19.71                    | HRS  |

Table 4

| JD−2450000 | Velocity (m s$^{-1}$) | Uncertainty (m s$^{-1}$) |
|-------------|-----------------------|--------------------------|
| 6374.88737  | −4.3                  | 1.2                      |
| 6375.91758  | 1.9                   | 1.1                      |
| 6376.93270  | 0.0                   | 1.1                      |
| 6377.98528  | −2.0                  | 1.2                      |
| 6399.91709  | 13.0                  | 1.4                      |
| 6526.29116  | 70.0                  | 1.4                      |
| 6529.31433  | 85.4                  | 1.5                      |
| 6555.29760  | 63.2                  | 1.5                      |
| 6556.21605  | 67.5                  | 1.5                      |
| 6686.00004  | −17.2                 | 1.6                      |
| 6744.92245  | −42.0                 | 1.5                      |
| 6747.92675  | −46.0                 | 1.6                      |
| 6764.87970  | −40.9                 | 1.3                      |

Figure 4. Upper: radial velocities of HD 47366 obtained with HIDES-S (red), HIDES-F (blue), CES-O (brown), CES-N (magenta), HRS (cyan), and AAT (green). The error bar for each point includes the extra Gaussian noise. The double Keplerian model for the radial velocities is shown by the solid line. Bottom: residuals to the Keplerian fit.

Figure 5. Phased radial velocities and the Keplerian models for the inner (upper panel; signal of the outer planet is removed) and the outer (bottom panel; signal of the inner planet is removed) planet. The error bar for each point includes the extra Gaussian noise. The symbols are the same as those in Figure 4.

the first 10% of which were discarded, and confirmed that each parameter was sufficiently converged based on the Gelman-Rubin statistic (Gelman & Rubin 1992). We derived the median value of the merged posterior PDF for each parameter and set a 1σ uncertainty as the range between 15.87% and 84.13% of the PDF.

In Figures 4 and 5, we plot the derived Keplerian orbits together with the radial-velocity points and their measurement errors including the extra Gaussian noises. The inner planet (planet b) has orbital parameters of a period of $P_b = 363.3^{+2.5}_{-2.3}$ days, an eccentricity of $e_b = 0.089^{+0.060}_{-0.079}$, a minimum mass of $m_b \sin i = 1.75^{+0.20}_{-0.17} M_J$, and a semimajor axis of $a_b = 1.214^{+0.030}_{-0.029}$ au, and the outer planet (planet c) has $P_c = 684.7^{+5.0}_{-4.9}$ days, $e_c = 0.278^{+0.067}_{-0.094}$, $m_c \sin i = 1.86^{+0.16}_{-0.15} M_J$. 

Table 4 AAT Radial Velocities for HD 47366

| JD−2450000 | Velocity (m s$^{-1}$) | Uncertainty (m s$^{-1}$) |
|-------------|-----------------------|--------------------------|
| 6374.88737  | −4.3                  | 1.2                      |
| 6375.91758  | 1.9                   | 1.1                      |
| 6376.93270  | 0.0                   | 1.1                      |
| 6377.98528  | −2.0                  | 1.2                      |
| 6399.91709  | 13.0                  | 1.4                      |
| 6526.29116  | 70.0                  | 1.4                      |
| 6529.31433  | 85.4                  | 1.5                      |
| 6555.29760  | 63.2                  | 1.5                      |
| 6556.21605  | 67.5                  | 1.5                      |
| 6686.00004  | −17.2                 | 1.6                      |
| 6744.92245  | −42.0                 | 1.5                      |
| 6747.92675  | −46.0                 | 1.6                      |
| 6764.87970  | −40.9                 | 1.3                      |
Table 5
Orbital Parameters for HD 47366

| Parameter                  | HD 47366 | HD 47366 c |
|----------------------------|----------|-----------|
| Period P (days)            | 363.3±3.5| 684.7±5.8 |
| RV semi-amplitude K1 (m s⁻¹)| 33.6±1.6 | 30.1±2.1  |
| Eccentricity e             | 0.089±0.079 | 0.278±0.067 |
| Longitude of periastron ω (deg) | 100±100 | 132±17   |
| Periastron passage Tp (JD—2450000) | 122±13 | 445±75  |
| Minimum mass m₂ sin i (M₂) | 1.75±0.20 | 1.86±0.15 |
| Semimajor axis a (au)      | 1.214±0.030 | 1.853±0.045 |

Note. Velocity offsets are the values relative to HIDES-S data.

and a_c = 1.853±0.045 au. The obtained parameters are listed in Table 5.

The *Hipparcos* satellite made a total of 158 photometric observations for HD 47366 from 1990 March to 1993 March, and revealed photometric stability for the star down to σ_HIP = 0.007 mag, though the *Hipparcos* observations were not contemporaneous with the radial-velocity observations. Figure 6 shows the generalized Lomb–Scargle periodogram (Zechmeister & Kürster 2009) of the *Hipparcos* photometric data of the star. We did not find any clue that the radial-velocity variations correlate with the brightness variations of the star. Thus the rotational modulation of spots on the stellar surface is not considered to be a viable explanation for the observed radial-velocity variations.

We also performed a spectral line shape analysis for the star, following the method in Sato et al. (2007). Cross-correlation profiles between pairs of stellar templates, each of which were extracted from five I2-supersposed spectra at phases of velocity ~30 m s⁻¹ (phase 1), ~10 m s⁻¹ (phase 2), and ~50 m s⁻¹ (phase 3) by using the method of Sato et al. (2002), were derived for about 110 spectral segments (4–5 Å width each). Three bisection quantities of the cross-correlation profiles, BVS, BVC, and BVD, were then calculated, which are the velocity difference between the two flux levels of the bisector, the difference of the BVS of the upper and lower halves of the bisector, and the average of the bisection at three flux levels, respectively. The flux levels of 25\%, 50\%, and 75\% of each cross-correlation profile were used to calculate the above three bisection quantities. As a result, we obtained BVS = 6.6 ± 5.5 m s⁻¹, BVC = −2.5 ± 3.0 m s⁻¹, and BVD = −86.1 ± 10.8 m s⁻¹ for the cross-correlation profile between phases 1 and 2, and BVS = −41.1 ± 4.9 m s⁻¹, BVC = 3.1 ± 2.6 m s⁻¹, and BVD = −35.1 ± 11.6 m s⁻¹ for the one between phases 2 and 3. The BVD values are consistent with the velocity differences between the phases, and the BVS and BVC values are much smaller than the BVD values. Therefore, we conclude that the observed radial-velocity variations did not originate from the distortion of the spectral lines, but from parallel shifts, as expected for orbital motion.

5. DYNAMICAL STABILITY

The orbital parameters obtained in Section 4 were derived by fitting a double Keplerian model to the radial-velocity data, which does not guarantee that the orbits are stable over long periods of time. In order to investigate the orbital stability of the system and to further constrain orbital parameters, we performed a dynamical analysis of the system. We used a fourth-order Hermite scheme for the numerical integration (Kokubo et al. 1998). Figure 7 shows the lifetime of the system, calculated by the 10⁵-year integrations. The lifetime here is defined as the time elapsing before the semimajor axis of one planet deviates by 10% from its initial value. All of the initial orbital parameters for the orbital integrations are fixed to the best-fit ones derived in Section 4 except for those shown in each axis of each panel. Figures 7(a)–(c) shows the lifetime of the system in the (aₚ, eₚ), (a_c, ω_c), and (ω_c, e_c) planes, respectively. In the panels, prograde and edge-on orbits (i₀ = i_c = 90°) are assumed. The dashed line in panel (a) shows the orbit-crossing boundary where the apocenter distance of planet b is equal to the pericenter distance of planet c. The planets b and c actually have almost crossing orbits with each other in the case of the best-fit orbits (marked by a red cross in each panel), and, as shown in the figure, they are unstable. Orbits above the boundary line easily become unstable within 1000 years. Stable orbits appearing above the boundary are in the 2:1 mean-
motion resonance. If \( a_c \) is near 1.93 au with an appropriate argument of pericenter, the orbits are stable with up to \( e_c \approx 0.7 \) over \( 10^9 \) years thanks to the resonance, though this \( a_c \) value is beyond the 3\( \sigma \) range of \( a_b/a_c = (0.6555^{+0.0081}_{-0.0074}) \) that is well determined by our radial-velocity data (panel (b)). On the other hand, if \( e_c \) is smaller than \( \sim 0.15 \) (1.4\( \sigma \) away from the best-fit value), the orbits are also stable even with the best-fit \( a_c \) (1.85 au) in prograde configuration (panel (c)).

If the mutual inclination \( i_{\text{mut}} \) between the two planets is higher than 160°, the orbit becomes stable in a wider parameter range. Figure 7(d) shows the stability map in the plane of inclination \( i_c \) and the ascending node \( (\Omega_c) \) of planet c (ascending node of planet b is set to \( \Omega_b = 0 \)). The mutual inclination of planets depends on \( i_b \), \( i_c \), and \( \Omega_c - \Omega_b \), as \( \cos i_{\text{mut}} = \cos i_b \cos i_c + \sin i_b \sin i_c \cos (\Omega_c - \Omega_b) \), and its contours are shown by black or purple lines in the figure. Since the absolute masses of the planets depend on the angle from the line of sight, the cases of three different inclinations for planet b, \( i_b = 30°, 60°, \) and \( 90° \), are shown. The absolute mass of planet c is also changed according to \( i_c \). The absolute masses of planets b and c are inversely proportional to \( \sin i_b \) and \( \sin i_c \), respectively. As seen in the figure, the orbits with \( i_{\text{mut}} \sim 180° \) (i.e., mutually retrograde) are stable in all cases. This is because planet encounters occur in a shorter time with higher mutual velocities in the retrograde system compared to the prograde system. This is similar to the case of the two brown-dwarf candidates orbiting BD+20 2457, in which the system is unstable for the prograde orbits, while it is stable for the retrograde orbits (Horner et al. 2014).

Figure 8 shows the \( 7 \times 10^4 \) year evolution of the system. The upper panel shows the evolution of the coplanar retrograde system with the best-fit orbital parameters derived in Section 4. Although the outer planet violates the orbit of the inner planet, they are stable over \( 10^6 \) years. The bottom panel shows a prograde case with the same orbital parameters except assuming \( e_c, i_{\text{ini}} \) = 0. As seen in the figure, if the eccentricity of the outer planet is small, the system can keep stable orbits, while the system with the outer planet in eccentric orbit quickly causes orbital crossing and becomes unstable (see Figure 7).

Figure 9 shows maps of the stability index \( D = |\langle n_2 \rangle - \langle n_1 \rangle| \) for the system. From a 5000-year numerical
integration, we obtain an average of mean motion \( \langle n_c \rangle \) of planet c and subtract it from an average of mean motion \( \langle n_b \rangle \) obtained in the next 5000-year orbit (see Couetdic et al. 2010 for the details of the stability analysis). The left and right panels are the maps for prograde and retrograde configuration, respectively. From a comparison with panel (a) of Figure 7, we find that the system is regular when \( \log R/D \leq -3 \). In the case of the retrograde orbit, the orbit is stable even if the eccentricity of the planet c exceeds the orbit-crossing boundary (dashed line) by \( \sim 0.1 \).

6. DISCUSSION AND SUMMARY

We have reported the detection of a double giant-planet system around the K1 giant HD 47366 \((M_\star = 1.81 \pm 0.13 \, M_\odot, \, R_\star = 7.30 \pm 0.33 \, R_\odot)\) from precise radial-velocity measurements at OAO, Xinglong, and AAT. The inner (planet b) and outer planets (planet c) have minimum masses of \( 1.75^{+0.20}_{-0.17} \, M_J \) and \( 1.80^{+0.16}_{-0.15} \, M_J \), semimajor axes of \( 1.21^{+0.10}_{-0.09} \, \text{au} \) and \( 1.85^{+0.05}_{-0.04} \, \text{au} \), and eccentricities of \( 0.089^{+0.079}_{-0.060} \) and \( 0.278^{+0.067}_{-0.094} \), respectively, which were derived by fitting a double Keplerian model to the radial-velocity data. The period ratio of the two planets is slightly smaller than 2, and thus the system adds to the growing population of such multi-giant-planet systems with small orbital separation around evolved intermediate-mass stars.

The dynamical analysis of the system revealed, however, that the best-fit orbits in prograde configuration are unstable. We found that it is stable in the following cases: (1) the two planets are in the 2:1 mean-motion resonance, (2) the eccentricity of planet c is less than \( 0.15 \), (3) the mutual inclination the two planets is larger than \( 160^\circ \) (i.e., retrograde configuration).

If the two planets are in the stable 2:1 resonance, the ratio of the semimajor axis should be \( a_b/a_c \sim 0.63 \) \((a_c \sim 1.93 \, \text{au})\) and the eccentricity of planet c should be \( 0.5 \leq e_c \leq 0.7 \) or \( 0 \leq e_c \leq 0.2 \) (see Section 5 and the darkest-blue regions in panel (a) of Figure 7). On the other hand, \( a_b/a_c \) is well determined from our observations to be \( a_b/a_c = 0.6555^{+0.0041}_{-0.0034} \) and \( e_c \) is determined to be \( e_c = 0.278^{+0.067}_{-0.094} \). Both of these values deviate from those for the high-eccentricity case with more than \( 3r \), and thus from the view point of the observational data, it is less likely that the planets are in the high-eccentricity resonance. We cannot completely reject the possibility of the low-eccentricity case. However, considering the semimajor-axis ratio, it is also less likely that the planets are in the resonance.

It is more plausible that the eccentricity of planet c is less than \( -0.15 \). The value is just \( 1.4r \) from the best-fit value, and the best-fit orbit is consistent with a circular one to the \( 3r \) level. Thus, it is reasonable to think that the two planets actually have nearly circular orbits and thus they are stable. In this case, the period ratio of the planets is slightly smaller than 2, and they are not in 2:1 resonance.

The third possibility is the most extreme one. Basically, we cannot determine the inclination or the ascending node of a planetary orbit by radial-velocity measurements, and thus we cannot discriminate between prograde and retrograde orbits observationally. Gayon & Bois (2008) and Gayon-Markt & Bois (2009) studied mutually retrograde configurations for some multi-planet systems around solar-type stars and showed that the configurations are dynamically stable and consistent with the radial-velocity observations. Recently, Horner et al. (2014) studied the dynamical stability of a double brown-dwarf system around the giant BD+20 2457 (Niedzielski et al. 2009), and showed that the prograde orbits best-fitted to the radial-velocity data are unstable, while those in retrograde configuration are stable. The HD 47366 system is similar to the case of the BD+20 2457 system. Our dynamical analysis showed that the coplanar retrograde configuration for the HD 47366 system is stable in a wider range of orbital parameters including the eccentric ones which are unstable for prograde configuration (see Figure 8). Confirmation of the high eccentricity of the outer planet by continuous observations will strongly support the retrograde hypothesis for the HD 47366 system, though the formation mechanism of such a mutually retrograde system is largely unknown. In any of the above cases, the planetary orbits can be altered by the close encounter of the planets in a relatively short period of time, and thus more detailed dynamical modeling for the observed radial-velocity variations is necessary in order to provide a definitive orbital solution.

The stellar and planetary parameters of HD 47366 system are similar to those of the \( \eta \) Cet system; two massive planets \((m_b, m_c) = (2.6 \, M_J, \, 3.3 \, M_J)\), with periods of \( P_b = 407 \) days and \( P_c = 740 \) days and eccentricities of \( e_b = 0.12 \) and \( e_c = 0.08 \) orbit around a K giant star with a mass of \( 1.7 \, M_\odot \) and a radius of \( 14.3 \, R_\odot \) (Trifonov et al. 2014). Trifonov et al. (2014) revealed that, for a coplanar configuration, the system can be stable by being trapped in an anti-aligned 2:1 mean-motion resonance in a region with moderate \( e_b \) eccentricity, which lies about \( \sigma \) away from the best-fit Keplerian orbits. A much larger non-resonant stable region also exists in low-eccentricity parameter space, though it appears to be much farther from the best fit than the 2:1 resonant region. This is in contrast with the case of HD 47366 in which low eccentricities of the planets are more plausible than 2:1 resonant configuration. Another possible 2:1 resonant system around an evolved star is 24 Sex, in which two massive planets \((m_b, m_c) = (1.99 \, M_J, \, 0.86 \, M_J)\), with periods of \( P_b = 452.8 \) days and \( P_c = 883.0 \) days and eccentricities of \( e_b = 0.09 \) and \( e_c = 0.29 \) orbit around a G-type subgiant with a
The Astrophysical Journal, 819:59 (11pp), 2016 March 1

Sato et al.

Figure 9. Mean motion diffusion $D$ (stability index) of the HD 47366 system. The best-fit orbital parameters are used as the initial parameters for the orbital integrations except for the semimajor axis and eccentricity of planet c, whose best-fitted values are marked by red crosses with their 1σ errors. The absolute mass of planets used in the simulations are $M_b = 1.75 M_J$ and $M_c = 1.86 M_J (i_b = i_c = 90^\circ)$. The dashed lines show the orbit-crossing boundary where the apocenter distance of planet b is equal to the pericenter distance of planet c. (a) Prograde coplanar configuration. (b) Retrograde coplanar configuration.

mass of 1.54 $M_J$ and a radius of 4.9 $R_J$ (Johnson et al. 2011). The period ratio of the planets is the closest to two of the three systems. Wittenmyer et al. (2012a) revealed that the best-fit orbit of the system is mutually crossing and it is only dynamically feasible if the planets are in 2:1 resonance, which can protect them from close encounters. As described, all of the above three systems are near the 2:1 resonance, but they show different properties in their orbital configuration. Further analysis and comparison of the systems would help us understand the dynamics of planetary systems in more detail.

It is unknown why multi-giant-planet systems with small orbital separations are preferentially found around evolved intermediate-mass stars (see Figure 1). It may be a primordial property of planets around intermediate-mass stars that could be an outcome of planet formation or an acquired one as a result of orbital evolution caused by stellar evolution (stellar tide and mass loss) of central stars. In the case of HD 47366, if the star is a helium-core burning star that has passed through the RGB tip (see Section 2), the planetary orbits could have been migrated outward by $\sim 10\%$ ($\sim 0.1$ au) during the RGB phase because of the effect of mass loss of the central star (Kunitomo et al. 2011; Villaver et al. 2014). However, the effect works for both of the two planets and thus it could not result in making the orbital separation smaller. The star might have harbored a third planet that was engulfed and possibly partially responsible for the current orbital configuration, though the star does not exhibit a possible signature of the planet engulfment such as an overabundance of lithium (e.g., Siess & Livio 1999; Adamow et al. 2012), Liu et al. (2014) obtained the lithium abundance of $^{17}\text{Li} = 0.38$ for HD 47366, suggesting that the star is an Li-depleted giant. Considering also that many of the systems with small orbital separation are found around less evolved subgiants, the effect of stellar evolution may be less significant compared to that of stellar mass. Unfortunately, the ongoing Doppler planet searches cannot clearly discriminate between the above two factors, stellar mass and stellar evolution, because the targets of the searches are both evolved and intermediate-mass stars. Investigating planets around intermediate-mass, main-sequence stars or those around evolved low-mass ($\sim 1 M_J$) stars would help clarify each effect separately.

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\footnote{$^{17}\text{Li} = \log n_{^{17}\text{Li}}/n_{\text{H}} + 12.$}
