ABSTRACT

We report the detections of a giant planet (MARVELS-7b) and a brown dwarf (BD) candidate (MARVELS-7c) around the primary star in the close binary system, HD 87646. To the best of our knowledge, it is the first close binary system with more than one substellar circumpri mary companion that has been discovered. The detection of this giant planet was accomplished using the first multi-object Doppler instrument (KeckET) at the Sloan Digital Sky Survey (SDSS) telescope. Subsequent radial velocity observations using the Exoplanet Tracker at the Kitt Peak National Observatory, the High Resolution Spectrograph at the Hobby Eberley telescope, the “Classic” spectrograph at the Automatic Spectroscopic Telescope at the Fairborn Observatory, and MARVELS from SDSS-III confirmed this giant planet discovery and revealed the existence of a long-period BD in this binary. HD 87646 is a close binary with a separation of ~22 au between the two stars, estimated using the Hipparcos catalog and our newly acquired AO image from PALAO on the 200 inch Hale Telescope at Palomar. The primary star in the binary, HD 87646A, has $T_{\text{eff}} = 5770 \pm 80$ K, log $g = 4.1 \pm 0.1$, and [Fe/H] = $-0.17 \pm 0.08$. The derived minimum masses of the two substellar companions of HD 87646A are $12.4 \pm 0.7 M_{\text{Jup}}$ and $57.0 \pm 3.7 M_{\text{Jup}}$. The periods are $13.481 \pm 0.001$ days and $674 \pm 4$ days and the measured eccentricities are $0.05 \pm 0.02$ and $0.50 \pm 0.02$ respectively. Our dynamical simulations show that the system is stable if the binary orbit has a large semimajor axis and a low eccentricity, which can be verified with future astrometry observations.

Key words: binaries: close – brown dwarfs – planetary systems

Supporting material: machine-readable table
1. INTRODUCTION

One of the most surprising astronomical developments of the last 25 years has been the discovery of an abundant population of extrasolar planets and brown dwarfs (BDs; Wolszczan & Frail 1992; Mayor & Queloz 1995; Nakajima et al. 1995; Rebolo et al. 1995). Radial velocity (RV) surveys to date have detected over 500 extrasolar planets (Han et al. 2014). The classical planet formation paradigm, which suggests that giant planets form and reside only in circular orbits at large distances from their parent stars, works well for our solar system, but not for extrasolar planetary systems. These RV extrasolar planets reveal an astonishing diversity of masses, semimajor axes, and eccentricities, from the short-period hot Jupiters, to planets in very elongated orbits, to planetary systems with multiple Jupiter-mass planets, to the super-Earth-mass planets with orbital periods of a few days (Butler et al. 2004; McArthur et al. 2004; Santos et al. 2004; Rivera et al. 2005; Lovis et al. 2006; Udry et al. 2006; Howard et al. 2010, 2014). Indeed, if any single statement captures the developments of this field, it is that the observations have continually revealed an unanticipated diversity of planetary systems.

Despite the fact that over 500 known exoplanets have provided important information about planet masses and orbital parameters, many more exoplanets are urgently needed for statistical characterization of emerging classes of planets and tests of detailed theoretical models for planet formation and evolution. A large planet sample is also needed to study the correlation between the presence of planets and stellar properties, such as metallicity, mass, multiplicity, age, evolutionary stage, activity level, and rotation velocity, not to mention the discovery of new planet populations. The growing need for more exoplanet samples triggered the development of multi-object Doppler technology at the University of Florida in 2004–2008. The first full-scale, multi-object exoplanet tracker instrument, the W.M. Keck Exoplanet Tracker (KeckET), was constructed in 2005 August–2006 February with support from the Keck Foundation. It was coupled with a wide field Sloan Digital Sky Survey telescope (SDSS, Gunn et al. 2006) and used for the pilot Multi-Object APO RV Exoplanet Large-Area Survey (MARVELS; Ge et al. 2008, Ge et al. 2009; Ge & Eisenstein 2009) in 2006–2007 (Fleming et al. 2010; Eisenstein et al. 2011).

This is the sixth paper in this series, examining the low-mass companions around solar-type stars from the SDSS-III MARVELS survey (Wisniewski et al. 2012; Fleming et al. 2012; De Lee et al. 2013; Jiang et al. 2013; Ma et al. 2013). In this paper, we present our discovery of two substellar companions, a giant planet (MARVELS-7b), and a BD (MARVELS-7c) around the primary star in a binary system, HD 87646, from the MARVELS pilot planet survey program. Section 2 reviews our previous knowledge of HD 87646. Section 3 introduces a brief description of the multi-object Doppler instrument and the pilot survey. Section 4 summarizes the survey data processing pipeline, Section 5 describes additional observations of the system, and Section 6 gives details of the results. Section 7 presents the main results and a discussion.

2. HD 87646

The target star, HD 87646, is a bright (V = 8) G-type star with a fainter K-type stellar companion at a separation of 0.213 arcsec and a position angle (PA) of 136° according to the Hipparcos and Tycho Catalogs (Perryman 1997). Its Hipparcos parallax of 13.59 ± 1.58 mas places it at a distance of 73.58 ± 9.68 pc. Photometry and high-resolution spectroscopic observations of HD 87646A have been obtained by Feltzing & Gustafsson (1998). They obtained an effective temperature of $T_{\text{eff}} = 5961$ K from photometry, and spectroscopically derived $\log g = 4.41$ and $[\text{Fe/H}] = 0.3$. This star is quite metal-rich, prompting Gonzalez et al. (2001) to explicitly recommend that it be observed with precise RV instruments due to the significantly higher probability of discovering hot-Jupiter planets around metal-rich stars (Fischer & Valenti 2005). While HD 87646 was observed as part of the Geneva Copenhagen Survey (Nordstrom et al. 2008), we are presently unaware of any high-precision RV observations, or of the star being part of any ongoing surveys.

Such binary systems are challenging for precise RV detection due to the complexity of analyzing spectra from two different stars. While detections of exoplanets in unresolved stellar binaries have been reported before (Konacki 2005), higher precision observations and a better cadence have not detected the same signal (Eggenberger et al. 2007). We speculate that this difficulty in detection is the reason this target was not observed in some ongoing surveys, such as N2K (Robinson et al. 2006), that are targeting high-metallicity stars. Multi-object surveys do not need to be as selective due to their inherent multiplicity advantage. Binaries may be excluded, but the existence of a few binaries among 60 stars observed simultaneously is not a significant problem. In addition, once observations are well underway there is little advantage gained in removing the target since any replacement target would then only be observed for a few epochs. We will study the impact of spectral contamination from a faint companion star on the RV measurements for our target in Section 6.2. Our study shows that the only substellar companions that can be detected in such close binaries are those massive enough to generate RV signals much larger than the noise induced by the spectral contamination.

3. THE MULTI-OBJECT KECKET PILOT SURVEY

The design of KeckET is based on a single object Exoplanet Tracker (ET) design for the KPNO 2.1 m telescope (Ge et al. 2003, Ge et al. 2006a, Mahadevan et al. 2008). This instrument adopts the dispersed fixed-delay interferometry (DFDI) approach for Doppler measurements (Erskine & Ge 2000; Ge 2002; Ge et al. 2002). Instead of the line centroid shifts in the high-resolution cross-dispersed echelle spectrograph approach, the DFDI method measures the Doppler motion by monitoring the fringe shifts of stellar absorption lines created by a Michelson-type interferometer with a fixed-delay between the two interferometer arms. The measurement of this fixed-delay is described in Wang et al. (2012a, 2012b).

The KeckET instrument consists of eight subsystems—a multi-object fiber feed, an iodine cell, a fixed-delay interferometer system, a slit, a collimator, a grating, a camera, and a 4k × 4k CCD detector. In addition, it contains four auxiliary subsystems: the interferometer control, an instrument calibration system, a photon flux monitoring system, and a thermal probe and control system. The instrument is fed with 60 fibers with 200 μm core diameters, which are coupled to 180 μm core diameter short fibers from the SDSS telescope, corresponding to 3 arcsec on the sky at f/5 (Ge et al. 2006b). The resolving
power for the spectrograph is $R = 5100$, and the wavelength coverage is $\sim 900$ Å, centered at 5400 Å. Details of the instrument design can be found in Ge et al. (2006b), Wan et al. (2006), and Zhao & Ge (2006). KeckET has one spectrograph and one 4k $\times$ 4k CCD camera that captures one of the two interferometer outputs, and has a 5.5% detection efficiency from the telescope to the detector without the iodine cell under the typical APO seeing conditions ($\sim 1.5$ arcsec seeing). The CCD camera records fringing spectra from 59 objects in a single exposure.

KeckET was commissioned at the SDSS telescope in Spring 2006. After a few engineering upgrades in Fall 2006, we conducted a pilot planet survey of 700 FGK main-sequence stars in 12 fields with $V$ = 7.6–12 to detect new planets in 2006 December to 2007 May. A total of 5–25 RV measurements have been obtained for the survey stars. The data were processed by a modified version of the data pipeline for the KPNO ET (Ge et al. 2006a). The instrument Doppler precision was measured with the day sky scattered light, which offers a stable, homogeneous RV source for simultaneously calibrating the instrument performance for all of the sky fibers. The rms error averaged over the 59 fibers, measured from the dispersion of measurements over a several-hour interval in 2006 November, is $6.3 \pm 1.3$ m s$^{-1}$. The corresponding average photon-limit error is $5.5 \pm 0.5$ m s$^{-1}$. The instrument’s precision over longer time intervals has been measured with repeated observations of sky scattered light over a period of 45 days in Fall 2006, and 150 days in the winter/spring of 2007. The rms dispersion of RV measurements of the sky over these periods, after subtracting the photon limiting errors in quadrature, are $11.7 \pm 2.7$ m s$^{-1}$ and $11.3 \pm 2.5$ m s$^{-1}$, respectively.

The instrumental contributions to random measurement errors are mainly caused by inhomogeneous illumination of the slit, image aberration, and the interferometer comb aliasing (sampling on the detector). However, the dominant measurement RV error is produced by the mathematical approximation used for extracting iodine and stellar Doppler signals in the mixed stellar and iodine fringing spectra, which is on the order of 50 m s$^{-1}$ (van Eyken et al. 2010) and is included in the RV errors showing in the data table. Although this error has largely limited our capability of detecting relatively low-mass planets, it does not affect the Doppler detection of massive giant planets, BDs, and binaries.

### 4. SURVEY DATA PROCESSING AND RV RESULTS

The pipeline processing steps are described in detail in van Eyken et al. (2004), Ge et al. (2006a), Mahadevan et al. (2008), and van Eyken et al. (2010). The data were processed using standard IRAF procedures (Tody 1993), as well as software written in IDL. The images were corrected for biases, dark current, and scattered light and then trimmed, illumination corrected, slant corrected, and low-pass filtered. The visibilities ($V$) and the phases ($\theta$) of the fringes were determined for each channel by fitting a sine wave to each column of pixels in the slit direction. To determine differential velocity shifts the star + iodine data can be considered as a summation of the complex visibilities ($V = V_i e^{i\theta_i}$) of the relevant star ($V_s e^{i\theta_s}$) and iodine ($V_i e^{i\theta_i}$) templates (Erskine 2003; van Eyken et al. 2004, 2010). For small velocity shifts, the complex visibility of the data, for each wavelength channel, can be written as

$$V_p e^{i\theta_p} = V_s e^{i\theta_s} e^{i\phi_s - i\phi_0} + V_i e^{i\theta_i} e^{i\phi_i - i\phi_0},$$

where $V_p$, $V_s$, and $V_i$ are the fringe visibilities for a given wavelength in the star + iodine data, star template, and iodine template, respectively, and $\theta_p$, $\theta_s$, and $\theta_i$ are the corresponding measured phases. In the presence of velocity shifts of the star and instrument drift, the complex visibilities of the star and iodine template best match the data with phase shifts of $\phi_s - \phi_0$, $\phi_i - \phi_0$, and $\phi_s - \phi_i$, respectively. The iodine is a stable reference and the iodine phase shift tracks the instrument drift. The difference between star and iodine shifts is the real phase shift of the star, $\Delta\phi$, corrected for any instrumental drifts

$$\Delta\phi = (\theta_s - \theta_0) - (\theta_i - \theta_0).$$

This phase shift can be converted to a velocity shift, $\Delta v$, using a known phase-to-velocity scaling factor:

$$\Delta v = \frac{c\lambda}{2\pi d}\Delta\phi,$$

where $c$ is the speed of light, $\lambda$ is the wavelength, and $d$ is the optical delay in the Michelson interferometer. The KeckET data analysis pipeline identifies the shift in phase of the star and iodine templates that are the best match for the data, and uses these phase shifts to calculate the velocity shift of the star relative to the stellar template. Since HD 87646 is a close binary system, we need an additional complex visibility term in Equation (1) to account for the contamination of the secondary star. Mathematically, this is equivalent to adding a small noise term $\delta \theta_k$ to the phase of the primary star $\theta_S$ (van Eyken et al. 2010), which will translate to the measured RV according to Equation (3). This noise term depends mainly on the flux ratio of the two stars collected through the fiber and the RV offset between the two stars. Thus this noise term varies slowly between observations. To simplify the RV fitting process, we

| Julian Date (UTC) | Velocity (m s$^{-1}$) | Velocity Error (m s$^{-1}$) |
|------------------|-----------------------|-----------------------------|
| 2454101.86236    | 21983                 | 52                          |
| 2454102.02955    | 22070                 | 54                          |
| 2454105.97151    | 21908                 | 53                          |
| 2454128.81306    | 21945                 | 52                          |
| 2454136.77204    | 20754                 | 52                          |
| 2454136.80788    | 20753                 | 51                          |
| 2454164.75013    | 20946                 | 53                          |
| 2454165.74965    | 20977                 | 52                          |
| 2454165.78557    | 20935                 | 52                          |
| 2454186.65127    | 22231                 | 51                          |
| 2454191.72256    | 21287                 | 53                          |
| 2454194.73526    | 21359                 | 53                          |
| 2454195.72733    | 21850                 | 52                          |
| 2454221.62148    | 21270                 | 51                          |
| 2454224.61552    | 23040                 | 52                          |
| 2454254.63197    | 21925                 | 55                          |

Note. A total of 16 observations are listed here. The rest and all the radial velocities from the other observatories are available as a machine readable table in the electronic edition.
treat this noise as a constant value and will study its impact on
the RV measurements of HD 87646 in Section 6.2. In practice,
one can try to model the visibility and phase of the secondary
star if both star spectra and their flux ratio variations with
wavelength are known precisely. This method is not very
practical in our current case because of this lack
of information.
We have obtained a total of 16 observations of HD 87646
using KeckET from 2006 December to 2007 June. The radial
velocities obtained are listed in Table 1.

5. FOLLOW-UP OBSERVATIONS

5.1. KPNO ET RV Observations

Subsequent observations were performed using the ET
instrument at KPNO (Ge et al. 2006a). Initial follow-up was
performed in 2007 November, which confirmed the variability
seen in the KeckET data. Additional data points were obtained
at KPNO in 2008 January, February, and May. The integration
time was 35–40 minutes in 2007 November and 20 minutes in
2008 January, February, and May.

The data were reduced using software described in
Mahadevan et al. (2008) and references therein. See van Eyken
et al. (2010) for the theory behind the technique. A total of 40
data points were obtained from 2007 November to 2008 May
and are also listed in Table 1. The observations confirmed the
linear trend shown in the KeckET data, which will be found
later due to another substellar companion.

5.2. Hobby Eberley Telescope (HET) RV Observations

Follow-up observations of HD 87646 were conducted with
the fiber-fed High Resolution Spectrograph (HRS, Tull 1998)
of the Hobby Eberley telescope (HET, Ramsey et al. 1998).
The observations were executed in queue scheduled mode
(Shetrone et al. 2007) and used a 2 arcsec fiber, with the HRS
slit set, to yield a spectral resolution of R \sim 60,000. A total of
29 data points were obtained between 2007 December and
2008 March. An iodine cell was inserted into the beam path
to yield a fiducial velocity reference. The radial velocities were
obtained using the procedure and analysis techniques described
in Marcy & Butler (1992). The HRS spectra consisted of 46
echelle orders recorded on the blue CCD (407–592 nm) and 24
orders on the red one (602–784 nm). The spectral data used for
RV measurements were extracted from the 17 orders (505
–592 nm) in which the I$_2$ cell superimposed strong absorption
lines. The radial velocities obtained are also provided in
Table 1.

5.3. MARVELS RV Observations

HD 87646 was selected as an RV survey target by the
MARVELS preselection criterion (Paegert et al. 2015). The star
has been monitored at 23 epochs using the MARVELS
instrument mounted on the SDSS 2.5 m Telescope at APO
between 2009 May and 2011 December (Ge et al. 2008, Ma
et al. 2013). The MARVELS instrument is a fiber-fed dispersed
fixed-delay interferometer instrument capable of observing 60
objects simultaneously and covers a wavelength range of
5000–5700 Å with a resolution of R \sim 12,000. The data
processing and error estimation algorithm have been described
in detail by Thomas et al. (2016). The final differential RV
products are included in the SDSS Data Release 12 (Alam
et al. 2015) and are presented in Table 1.

5.4. Fairborn RV Observations

To investigate the nature of the linear RV trend found in
previous RV data, we have obtained additional observations of
HD 87646 with a fiber-fed echelle spectrograph situated at the
2 m Automatic Spectroscopic Telescope (AST) in the Fairborn
Observatory (Eaton & Williamson 2004, 2007). The robotic
nature of the AST allowed for high cadence observations,
which removed orbital period degeneracies and helped solidify
the longer-period companion’s orbit. Through 2011 June, the
detector was a 2048 \times 4096 SITe ST-002A CCD with 15 \mu m
pixels. The AST echelle spectrograph has 21 orders that cover
the wavelength range of 4920–7100 Å, and has an average
resolution of 0.17 Å. Beginning in 2010 January, several
upgrades were made to increase the throughput, sensitivity, and
flexibility of the AST (Fekel et al. 2013). In the summer of
2011, the SITe CCD detector and dewar were replaced with a
Fairchild 486 CCD having 4K \times 4K 15 \mu m pixels, which
required a new readout electronics package, and a new dewar
with a Cryotiger refrigeration system. The echelle spectrograms
that were obtained with this new detector have 48 orders,
covering the wavelength range of 3800–8260 Å. The data
reduction and RV measurements are discussed in Eaton &
Williamson (2007). A total of 135 data points were obtained
from 2009 March through 2013 October and are listed in
Table 1. With these additional RV data, we were able to detect
the turnaround of the previous identified linear RV trend and
start to uncover the second substellar companion’s orbit.

5.5. TNG High-resolution Spectroscopy

A total of nine high-resolution spectra ($R = 164,000$) of
HD 87646 were obtained with the SARG spectrograph on the
3.5 m TNG telescope at La Palma on 2008 March 21, 22,
and 28, and April 03 and 11. These data were used to monitor
line bisector variations to determine stellar properties (metallic-
ity, log g, T$_{\text{eff}}$ and v sin i), and to search for evidence of
a second set of lines in the system. The typical signal-to-noise
ratio (S/N) for each spectrum is about 150 per resolution
element around 5500 Å.

5.6. KPNO EXPERT High-resolution Spectroscopy

We also obtained spectroscopic observations of HD 87646
from the 2.1 m telescope at the Kitt Peak National Observatory
using the $R = 30,000$ Direct Echelle Mode of the EXPERT
spectrograph (Ge et al. 2010). A total of seven EXPERT
spectra were acquired between 2014 February to 2014 June.
The exposure time for each observation ranged from 20 to 40
minutes, yielding an S/N $\sim 250$ per resolution element around
5500 Å.

5.7. Lucky Imaging

On 2008 May 29, high-angular-resolution lucky images of
HD 87646 were obtained with the FastCam instrument (Oscoz
et al. 2008) on the 2.5 m Nordic Optical Telescope at the Roque
de los Muchachos Observatory in La Palma (Spain). Five data
cubes of 1000 images each were obtained using the I-band
filter. Individual exposure times were 30 ms for each image.
High-spatial-resolution was obtained by combining the best 1%
of the images. Figure 1 shows the processed image. The image scale was 30.95 ± 0.05 mas pixel⁻¹. In this figure, the secondary star HD 87646B in this binary system is visible. The point-spread function (PSF) of the star has a full width half maximum (FWHM) value of 0.11.

5.8. Palomar AO Imaging

On 2009 June 4, we acquired high-resolution AO images of the binary star system HD 87646 from PALAO on the 200 inch Hale Telescope at Palomar. Data sets were taken in the J and K bands. The AO system was running at 500 Hz. The seeing was roughly 1.3 in the K band. We also observed a calibrator star and subtracted the K band’s PSF, which improved sensitivity by a factor of a few. The utility of PSF subtraction is limited, in this case, by the difference in stellar spectral types, since the filters are broad.

Images were flat-fielded, background subtracted, and cleaned; the final images are displayed on a logarithmic scale in Figure 2 with a scale of 25 mas pixel⁻¹. The binary system is well-resolved in both bands. The angular separation is 5.8 ± 0.1 arcsec. The images have a scale of 25 mas pixel⁻¹. The FWHMs are 70 mas and 120 mas for J- and K-band images respectively.

5.9. Automatic Photoelectric Telescope (APT) Photometry

Photometry of HD 87646 was obtained in the Stromgren b and y bands between 2007 December and 2015 June with the T12 0.8 m APT at Fairborn Observatory in Arizona. Our primary goal with photometry is to detect if the companions transit the primary star. The data were processed using software described in Henry (1999). The measurements have a typical accuracy of ~0.001 mag.

6. RESULTS

6.1. Stellar Parameters

The SARG spectra taken at TNG without the iodine cell were used to derive the stellar parameters. HD 87646 is flagged as a binary in the Hipparcos and Tycho Catalogs (Perryman 1997), with a Hipparcos magnitude (a broadband V filter) difference between the primary and secondary to be 2.66 ± 0.96 mag. Taking into account the binary nature of
the object, we explored possible combinations of stellar parameters for the primary and secondary. The SED and the colors change slightly due to the secondary contribution; however, the normalized spectra show minor changes, only affecting the wings of strong lines (e.g., the Mg b lines, Figure 3). The equivalent widths of most weak lines are essentially unchanged, so we used Fe I and Fe II lines with equivalent widths below 140 mÅ and performed a traditional spectroscopic analysis.

We use the latest MARCS model atmospheres (Gustafsson et al. 2008) for the analysis. Generation of synthetic spectra and the line analysis were performed using the turbospectrum code (Alvarez & Plez 1998), which employs line broadening according to the prescription of Barklem & O'Mara (1998). The line lists are drawn from a variety of sources. Atomic lines are taken mainly from the VALD database (Kupka et al. 1999). The molecular species CH, CN, OH, CaH, and TiO are provided by B. Plez (see Plez & Cohen 2005), while the NH, MgH, and C2 molecules are from the Kurucz line lists. The solar abundances used here are the same as Asplund (2005). We used the Fe I excitation equilibrium and derived an effective temperature \( T_{\text{eff}} = 5770 \pm 80 \text{ K} \), which is slightly lower than the effective temperature derived from photometry (Feltzing & Gustafsson 1998). The H\( \alpha \) and H\( \beta \) wings also agree better for this lower \( T_{\text{eff}} \) value. We find \( \log g = 4.1 \pm 0.1 \), based on the ionization equilibrium of Fe I and Fe II lines and by fitting the wings of the Mg b lines, which agrees with the previous estimates. A microturbulence value of 1.8 km s\(^{-1}\) is derived by forcing weak and strong Fe I lines to yield the same abundances. We are not able to confirm the super solar metallicity of this object (Feltzing & Gustafsson 1998); we derived \( \text{[Fe/H]} = -0.17 \pm 0.08 \). When we adopt the same \( T_{\text{eff}} \) and microturbulence as Feltzing & Gustafsson (1998), we obtain the same metallicity value of \( \text{[Fe/H]} = 0.3 \), but with a large slope in the excitation potential versus the Fe I abundance and the reduced equivalent width versus the Fe I abundance. The derived stellar parameters are summarized in Table 2.

We attempted to place constraints on the secondary star by fitting the Balmer line and Mg b line wings. Based on the \textit{Hipparcos} data, which suggest a \textit{Hipparcos} magnitude difference between the primary and secondary 2.66 \pm 0.96 mag, the secondary has a flux contribution of 8\%–10\% with respect to the primary. We synthesized binary spectra with a G-dwarf primary and a K-dwarf secondary, with 10\% and 50\% flux contributions from the secondary. The binary spectrum synthesis results are consistent with the \textit{Hipparcos} data with a 10\% contribution from the secondary. We cannot place better estimates based on the spectral line profiles because of the large errors in the continuum normalization of these lines, since they spread over the entire echelle order.

We use the empirical polynomial relations of Torres et al. (2010) to estimate the mass and radius of the primary star, HD 87646A, from \( T_{\text{eff}}, \log g, \) and [Fe/H]. These relations were derived from a sample of eclipsing binaries with precisely measured masses and radii. We estimate the uncertainties in \( M_\ast \) and \( R_\ast \) by propagating the uncertainties in \( T_{\text{eff}}, \log g, \) and [Fe/H] using the covariance matrices of the Torres et al. (2010) relations (kindly provided by G. Torres). Since the polynomial relations of Torres et al. (2010) were derived empirically, the relations were subject to some intrinsic scatter, which we add in quadrature to the uncertainties propagated from the stellar parameter measurements (\( \sigma_{\log M} = 0.027 \) and \( \sigma_{\log R} = 0.014; \) Torres et al. 2010). The final stellar mass and radius values obtained are \( M_\ast = 1.12 \pm 0.09 \, M_\odot \) and \( R_\ast = 1.55 \pm 0.22 \, R_\odot \).

### 6.2. Systematic RV Errors Due to the Blended Binary Spectrum

HD 87646 is a binary system, and contamination of the primary star’s spectrum by the secondary star leads to an increased RV jitter because it interferes with the analysis pipeline. In this section, we investigate the possible systematic RV errors caused by the blended binary spectra using simulations. Since our RV observations were produced by two different kinds of spectrographs, we decided to perform two simulations, one for the DFDI instruments, including KeckET, KPNO ET, and MARVELS, and the other for traditional echelle spectrographs, including HRS at HET and the AST fiber-fed echelle spectrograph at Fairborn. In both simulations, we first create a set of stellar spectra by combining a G-type star (for the primary) and a K-type (for the secondary) star spectra with varying radial velocities for both stars. Then we calculate the differential radial velocities for the G star from the simulated spectra. The differences between the output G-star RVs and input G-star RVs are the RV errors caused by secondary star spectra contamination. Both simulations yield similar RV errors on the order of 200 m s\(^{-1}\). We expect to see this level of systematic error and will include it in the RV “jitter” term when we perform the RV curve fitting in the next section. Traditionally, the “jitter” term is used to denote any RV noise caused by stellar activity; our “jitter” term also contains the RV noise caused by blended binary spectra.

### 6.3. RV Curve Fitting and Orbital Parameters

We have performed a Markov Chain Monte Carlo (MCMC) analysis of the combined RV observations from KeckET, ET, HET, MARVELS, and Fairborn instruments. In this analysis, we initially used a one planet RV model to fit our RV observations, and later found that there is another strong periodic RV signal in the RV residuals. We then adopted a two-object (a planet and a BD) RV model to fit our RV data. The RV model details are presented in Section 2 of Gregory (2007). We have attempted to add in another planet to fit our RV data around the third peak in the periodogram. The addition of another planet did not significantly improve our RV fitting. Furthermore, the fact that the newly added planet has a period half of the first giant planet and an eccentricity of 0.99, we consider it to be an alias and over-fit of the noise. Thus we have rejected the RV model with three substellar companions.
Throughout the paper, we only present and discuss the RV model with two substellar companions.

Each state in the Markov chain is described by the parameter set

$$\theta = \{ P_1, K_1, e_1, \omega_1, M_1, P_2, K_2, e_2, \omega_2, M_2, C_i, \sigma_{\text{jitter}} \},$$

where $P_1$ and $P_2$ are orbital periods, $K_1$ and $K_2$ are the RV semi-amplitudes, $e_1$ and $e_2$ are the orbital eccentricities, $\omega_1$ and $\omega_2$ are the arguments of periastron, $M_1$ and $M_2$ are the mean anomalies at chosen epoch ($\tau$), $C_i$ is the constant velocity offset between the differential RV data shown in Table 1 and the zero-point of the Keplerian RV model ($i = 1$ for KeckET observations, $i = 2$ for KPNO ET observations, $i = 3$ for HET observations, $i = 4$ for MARVELS observations, and $i = 5$ for Fairborn observations), and $\sigma_{\text{jitter}}$ is the “jitter” parameter. The jitter parameter describes any excess noise, including both astrophysical noise (e.g., stellar oscillation, stellar spots; Wright 2005), any instrument noise not accounted for in the quoted measurement uncertainties and systematic RV errors from analyzing blended binary spectra discussed in the last section. We use standard priors for each parameter (see Gregory 2007). The prior is uniform in the logarithm of the orbital period ($P_1$ and $P_2$) from 1 to 5000 days. For $K_1$, $K_2$, and $\sigma_{\text{jitter}}$, we use a modified Jefferys prior, which takes the form of

$$p(x) = (x + x_0)^{-1} \log(1 + x_{\text{max}}/x_0)^{-1},$$

where $x_0 = 0.1$ m s$^{-1}$ and $x_{\text{max}} = 2128$ m s$^{-1}$ (Gregory 2005). Priors for $e_1$ and $e_2$ are uniform between zero and unity. Priors for $\omega_1$, $\omega_2$, $M_1$, and $M_2$ are uniform between zero and $2\pi$. For $C_i$, the priors are uniform between min($v_i$) = 5 km s$^{-1}$ and max($v_i$) = 5 km s$^{-1}$, where $v_i$ is the set of radial velocities obtained from each of the four instruments ($i = 1$ for KeckET observations, $i = 2$ for KPNO ET observations, $i = 3$ for HET observations, $i = 4$ for MARVELS observation, and $i = 5$ for Fairborn observations). We verified that the chains did not approach the limiting values of $P_1$, $P_2$, $K_1$, $K_2$, and $\sigma_{\text{jitter}}$.

### Table 3

Orbital Parameters for HD 87646b and HD 87646c

| Parameter          | HD 87646b     | HD 87646c     |
|--------------------|---------------|---------------|
| Minimum mass       | $12.4 \pm 0.7 M_{\text{Jup}}$ | $57.0 \pm 3.7 M_{\text{Jup}}$ |
| $a$                | $0.117 \pm 0.003$ au | $1.58 \pm 0.04$ au |
| $K$                | 956 $\pm 25$ m s$^{-1}$ | 1370 $\pm 54$ m s$^{-1}$ |
| $P$                | 13.481 $\pm 0.001$ day | 674 $\pm 4$ day |
| $e$                | 0.05 $\pm 0.02$ | 0.50 $\pm 0.02$ |
| $\omega$ (radians) | 5.20 $\pm 0.52$ | 1.95 $\pm 0.06$ |
| $T_{\text{prediction for transit}}$ (JD$_{UTC}$) | 2454093.85 $\pm 0.12$ day | 2454088.3 $\pm 1.1$ day |
| $T_{\text{periastron}}$ (JD$_{UTC}$) | 2453707 $\pm 9$ day |
| $\sigma_{\text{jitter}}$ | 240 $\pm 12$ m s$^{-1}$ |
| $C_1$              | 20.878 $\pm 0.050$ km s$^{-1}$ |
| $C_2$              | 20.777 $\pm 0.090$ km s$^{-1}$ |
| $C_3$              | 0.908 $\pm 0.080$ km s$^{-1}$ |
| $C_4$              | $-0.306 \pm 0.050$ km s$^{-1}$ |
| $C_5$              | 20.786 $\pm 0.070$ km s$^{-1}$ |
| rms$_1$            | 245 m s$^{-1}$ |
| rms$_2$            | 248 m s$^{-1}$ |
| rms$_3$            | 261 m s$^{-1}$ |
| rms$_4$            | 270 m s$^{-1}$ |
| rms$_5$            | 312 m s$^{-1}$ |

Following Ford (2006), we adopt a likelihood (i.e., conditional probability of making the specified measurements given a particular set of model parameters) of

$$p(v | \theta, M) = \prod_k \frac{\exp[-(v_k - \hat{v}_k)^2 / 2(\sigma_{\text{obs}}^2 + \sigma_{\text{jitter}}^2)]}{\sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{jitter}}^2}},$$

where $v_k$ is observed RV at time $t_k$, $\hat{v}_k, \beta$ is the model velocity at time $t_k$ given the model parameters $\theta$, and $\sigma_{\text{obs}}$ is the measurement uncertainty for the RV observation at time $t_k$.

We combine the Markov chains described above to estimate the joint posterior probability distribution for the orbital model for HD 87646. In Table 3, we report the median value and an uncertainty estimate for each model parameter based on the marginal posterior probability distributions. The uncertainties
are calculated as the standard deviation about the mean value from the combined posterior sample. Since the shape of the marginal posterior distribution is roughly similar to a multivariate normal distribution, the median value plus or minus the reported uncertainty roughly corresponds to a 68.3% credible interval. In the same table, we also reported the rms of the RV fitting residuals for the five different RV instruments used here, which are $r_{\text{rms}} = 245$ m s$^{-1}$ for KeckET, $r_{\text{rms}} = 248$ m s$^{-1}$ for KPNO ET, $r_{\text{rms}} = 261$ m s$^{-1}$ for HET, $r_{\text{rms}} = 270$ m s$^{-1}$ for MARVELS, and $r_{\text{rms}} = 312$ m s$^{-1}$ for Fairborn RV observations.

This two-Keplerian orbital solution is shown in Figures 4 and 5 together with the KeckET, HET, KPNO ET, Fairborn, and MARVELS RV data. The residuals in these two plots cannot be explained only by the errors in our RV data. A stellar jitter term $\sigma_{\text{jitter}} = 240 \pm 12$ m s$^{-1}$ is required in our fitting to explain these residuals. As discussed in the last section, most of the “jitter” noise arises from our data pipeline handling the blended binary spectra instead of a single star spectra. We also did an MCMC analysis using two “jitter” noise terms, one for DFDI instruments and the other one for echelle spectrographs, and find the orbital parameters for the giant planet candidate and the BD candidate are barely changed within the error bars. Thus, to keep it simple, we choose to use one “jitter” term for all our RV observations from different instruments.

HD 87646 is a binary system, so we have done another MCMC analysis by including a linear RV trend ($v_{\text{trend}} \times (t - t_0)$) to the two-object RV model used above. This linear RV trend is used to account for the perturbation of the primary star induced by the gravitational force of the secondary star. We note here that the offsets between different data sets will hinder the modeling of this linear trend as there is expected strong correlation between the offsets and this linear trend. Our new RV fitting yields orbital parameters for the two substellar companions in addition to a linear RV trend of $v_{\text{trend}} = -12 \pm 18$ m s$^{-1}$ yr$^{-1}$, which are summarized in Table 4. Since all of the main orbital parameters of the two substellar companions are barely changed within their respective error bars and the strong correlation between this RV trend and telescope RV offsets, we decide to keep using the numbers present in Table 3 throughout this paper. This linear trend is not significant, which means it is more likely that either the secondary star is close to its ascending or descending node during 2008–2013, or this binary is on a relatively low-inclination (face on) orbit. It is not possible for us to distinguish these two scenarios using our current data. Future high-precision astrometry observations, such as GAIA, will help to solve this binary orbital problem. We also want to note here that this linear trend is not the exact real RV trend of the primary star induced by the gravitational perturbation of the secondary star because of the secondary star’s spectral contamination. It is close to $\sim 70$–80% of the real trend value assuming the flux ratio of the two stars is $\sim 10$ in the optical band and the mass ratio is $\sim 2$.

### 6.4. Line Bisector Analysis

Santos et al. (2002) found small RV variations and line asymmetries for the star HD 41004, which is a visual binary and unresolved at the spectrograph. It was initially thought to have a planetary companion around the primary star, but from the line bisector analysis they were able to infer a possible BD orbiting the secondary star instead of a planet orbiting the primary star. Their conclusions were subsequently corroborated by Zucker et al. (2003).

Similar to HD 41004, HD 87646 is also a binary system with a small angular separation (0.4"), which renders the spectrum a blended spectrum of the two stellar components. Following the same philosophy of Santos et al. (2002), we performed a bisector analysis for HD 87646 to determine from which star in the binary system the RV signal was produced. We have analyzed spectra taken at the Kitt Peak 2 m telescope using EXPERT (Ge et al. 2010). Spectra were reduced using an IDL pipeline modified from an earlier version described in Wang (2012). Frames were trimmed, bias subtracted, flat-field corrected, aperture-traced, and extracted. Cross-correlation functions (CCFS) are derived by cross-correlation with a spectral mask from the wavelength range of 4900–6300 Å. Then we compute the bisector velocity for 10 different levels of

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**Table 4**

Orbital Parameters for HD 87646b and HD 87646c with a Linear RV Trend

| Parameter          | HD 87646b   | HD 87646c   |
|--------------------|-------------|-------------|
| Minimum mass ($M_{\ast}$) | 12.4 ± 0.7   | 57.0 ± 3.7   |
| $u$                | 0.117 ± 0.003 au | 1.58 ± 0.04 au |
| $K$                | 954 ± 24 m s$^{-1}$ | 1370 ± 56 m s$^{-1}$ |
| $P$                | 13.481 ± 0.001 day | 673 ± 4 day   |
| $e$                | 0.05 ± 0.02     | 0.50 ± 0.02  |
| $\omega$ (radians) | 5.18 ± 0.48    | 1.95 ± 0.06  |
| $T_{\text{prediction for transit}}$ (JD$_{\text{UTC}}$) | 2454093.86 ± 0.14 day |
| $T_{\text{planets}}$ (JD$_{\text{UTC}}$) | 2454088.2 ± 1.0 day | 2453709 ± 8 day |

$v_{\text{trend}} = -12 \pm 18$ m s$^{-1}$ yr$^{-1}$, which are summarized in Table 4. Since all of the main orbital parameters of the two substellar companions are barely changed within their respective error bars and the strong correlation between this RV trend and telescope RV offsets, we decide to keep using the numbers present in Table 3 throughout this paper. This linear trend is not significant, which means it is more likely that either the secondary star is close to its ascending or descending node during 2008–2013, or this binary is on a relatively low-inclination (face on) orbit. It is not possible for us to distinguish these two scenarios using our current data. Future high-precision astrometry observations, such as GAIA, will help to solve this binary orbital problem. We also want to note here that this linear trend is not the exact real RV trend of the primary star induced by the gravitational perturbation of the secondary star because of the secondary star’s spectral contamination. It is close to $\sim 70$–80% of the real trend value assuming the flux ratio of the two stars is $\sim 10$ in the optical band and the mass ratio is $\sim 2$.
The central transit, with a depth of 0.005 mag and duration of 0.015 units of phase. The predicted central transit window. The solid curve shows the predicted time of mid-transit. Bottom: an expanded portion of the top plot, centered on the predicted central transit, phased at 0.5, for a duration of 0.21 days or 0.015 units of phase and a depth of 0.5% or ~0.005 mag. The ±1σ uncertainty in the transit window timing is indicated by the two vertical dotted lines.

the CCF. The values for the upper (near continuum) and lower bisector points are averaged and subtracted. The resulting quantity (the bisector inverse slope, BIS) can be used to measure the line bisector variations (Queloz et al. 2001). The result of the bisector analysis is presented in Figure 6, which demonstrates that the BIS varies in phase with the RV.

We then created two simulations following Santos et al. (2002), one by assuming a giant planet orbiting the primary star of the binary (solid line in Figure 6) and the other by assuming a heavier BD orbiting the secondary star (dotted line in Figure 6). Both scenarios can explain the RV curve seen for HD 87646, but clearly only the one in which the giant planet is orbiting the primary star (solid line in Figure 6) is consistent with the BIS analysis. Our conclusion from the BIS analysis is that the 13.5 day period giant planet is orbiting the primary star HD 87646A.

6.5. Photometry Results

The top panel of Figure 7 presents all 1077 photometric observations plotted against the latest transit ephemeris of HD 87646a: $T_c = 2454093.85$ day, $P = 13.481$ day. The differential magnitudes are measured against the mean of three comparison stars to improve precision. The standard deviation of these data from their mean is 0.0014 mag. A least-squares sine-curve fit to the phased data yields a full amplitude of 0.000089 ± 0.000065 mag. There is no detectable brightness variation on the short-period RV period; this result supports the interpretation that the observed RV variations are caused by a companion.

The bottom panel of Figure 7 is similar to the top panel except that it displays only the data within ±0.1 phase units from the predicted transit time. We also show the predicted central transit, phased at 0.5, for a duration of 0.21 days or ~0.015 units of phase and a depth of 0.5% or ~0.005 mag (Kane & von Braun 2008). The ±1σ uncertainty in the transit window timing is indicated by the two vertical dotted lines.

There are 1005 observation that lie outside the predicted transit window, which have a mean of 0.99998 ± 0.00005 mag and 72 observations that fell within the transit window have a mean of 1.0003 ± 0.0002 mag. The difference between these two mean brightnesses is 0.0003 ± 0.0002 mag. Full transits with a predicted depth of ~0.005 mag are excluded by the photometry at the predicted transit time.

6.6. Companion Inclination and Mass Estimate

The mass function is related to the observed period, eccentricity, and RV semi-amplitude as

$$\frac{(m \sin i)^3}{(M_\star + m)^2} = \frac{P (1 - e^2)^{3/2}K^3}{2 \pi G}$$

(6)

where $M_\star$ is the mass of the primary and $m$ is the mass of the companions. Since the first companion is known not to transit the star, we cannot break the degeneracy of mass and $\sin i$ with RV observations alone. Using the derived stellar mass (1.12$M_\odot$) for the primary with the orbital parameters determined from the RV (Table 3), we determine that the minimum mass of the inner companion for an edge-on orbit ($\sin i = 1$) is 12.4 ± 0.7 $M_{\text{Jup}}$. This mass is quite close to the deuterium burning limit, and the detected companion is likely burning deuterium, though its minimum mass places it in the giant planet regime. The second companion’s minimum mass, when assuming an edge-on orbit, is 57.0 ± 3.7 $M_{\text{Jup}}$, which falls right in the BD regime.

7. SUMMARY AND DISCUSSION

7.1. Summary of the Main Results

Our SDSS MARVELS pilot survey and additional observations at the HET, KPNO 2.1 m telescope, and Fairborn observatory confirm the detection of two massive substellar companions in a close binary system HD 87646. The first companion, HD 87646Ab, has a minimum mass of 12.4 ± 0.7 $M_{\text{Jup}}$, a period of 13.481 ± 0.001 days, and an eccentricity of 0.05 ± 0.02. The measured eccentricity is in line with other short-period giant planets in binaries (e.g., Eggenberger et al. 2007). This companion is likely to be a giant planet or a BD, depending on its inclination angle. Our bisector analysis has shown that this companion is in orbit around the primary star. The second companion has a minimum mass of 57 ± 3.7 $M_{\text{Jup}}$, a period of 674 ± 4 days, and an eccentricity of 0.50 ± 0.02. This companion is likely to be a BD. Ma & Ge (2014) have found that long-period, high-mass (>4$M_{\text{Jup}}$) BDs tend to have higher eccentricities. This new BD is consistent with this trend.

This is the eleventh detection of a substellar companion(s) in a binary system with a separation of only about 20 au. The other 10 systems are Gliese 86 (Queloz et al. 2000; Mugrauer & Neuhausen 2005; Lagrange et al. 2006), γ Cephei (Hatzes et al. 2003), HD 41004 (Zucker et al. 2003, 2004), HD 188753 (Konacki 2005), HD 176051 (Muterspaugh et al. 2010), HD 126614 (Howard et al. 2010), α Centauri (Dumusque et al. 2012), HD 196885 (Correia et al. 2008), OGLE-2013-BLG-0341 (Gould et al. 2014), and HD 59686 (Ortiz et al. 2016). However, Eggenberger et al. (2007) did not confirm the planet in HD 188753, and Rajpaul et al. (2016) suggest that the planet signal discovered from α Centauri B is not from a real
planet, but from the observation window function. To the best of our knowledge, HD 87646A is the first multiple planet/BD system detected in such close binaries.

7.2. Dynamical Stability of HD 87646

In this section, we will discuss the dynamical stability of the binary system HD 87646. First, we have collected observational data of HD 87646 from the literature (Horich et al. 2008, 2010; Hartkopf & Mason 2009; Balega et al. 2013) and combined them with our AO data to constrain the binary orbit of HD 87646. Our best-fitting binary orbital solution (solid line) and the observational data (black dots) are shown in Figure 8. The best-fitting parameters are \( P = 51.6 \text{ year}, e = 0.54, \) and \( a = 0.26 \text{ arcsec} \). At a distance of 73.58 ± 9.68 pc, this angular separation corresponds to a binary semimajor axis of 19 ± 2 au. Since the observational data only cover less than half of the binary orbit, these fitting parameters are very preliminary. There are many previous cases for which binary orbital parameters were revised significantly with new and better astrometry measurements, especially when the binary orbit is not yet completely determined by astrometry observations (Hartkopf & Mason 2009). Using the same classification of visual binaries as that in Hartkopf et al. (2001) for the Catalog of Visual Binary, our orbital solution has a grade of 4 (1—definitive, 2—good, 3—reliable, 4—preliminary, 5—indeterminate) and formal errors of the orbital solution were considered to have little meaning.

We then performed a numerical simulation of the binary system including the giant planet and BD discovered in this paper. The binary-planetary-BD system of HD 87646 is the first multiple planet/BD system detected in such close binaries. The dynamical stability of this system can be evaluated by fitting the astrometric data with a chi-squared of 1 after we rescale the error bars for astrometric data (see also Figure 8). The white triangle symbol shows the best binary orbital fit from the current astrometry data with \( \chi^2_{\text{red}} = 1 \). There is an overlap between the distribution of binary orbital parameters and the dynamically stable region, which demonstrates the binary system has stable orbital solutions.

7.3. Nature of the System and Its Formation and Evolution

HD 87646 is the first known system to have two massive substellar objects orbiting a star in a close binary system. Interestingly, the masses of these two substellar objects are close to the minimum masses for burning deuterium (~13 \( M_{\text{Jup}} \), Spiegel et al. 2011) and hydrogen (~75\( M_{\text{Jup}} \), Chabrier & Baraffe 2000), which are generally assumed to be the general mass boundaries between the planet and the BD and between the BD and the star, respectively. All of these peculiarities raise a question: how could such a system be formed? Here we briefly discuss this intriguing issue.

The large masses of these two substellar objects suggest that they could be formed as stars with their binary hosts: a large molecular cloud collapsed and fragmented into four pieces; the larger two successfully became stars and formed the HD 87646 binary, and the other smaller ones failed to form stars and became the substellar objects in this system (Chabrier et al. 2014). This scenario might be relevant for the binary stars but seems to be problematic for the two substellar objects on orbits within ~1 au because it is unclear whether fragmentation on such a small scale can occur (Kratter & Murray-Clay 2011).
Perhaps a more plausible explanation is that the two substellar objects were formed like a giant planet in a protoplanetary disk around HD 87646A. As for giant planet formation, there are currently two main models: core accretion versus disk instability (see the review by D’Angelo et al. 2010; Helless et al. 2014). Recently, many studies have examined the core accretion model’s ability to form planets in close binaries with separations of ~20 au (see the review by Thebault & Haghighipour 2014, and references therein). A commonly recognized issue is that the binary perturbations generally inhibit the growth of planetesimals in the disk (Thebault 2011). Even if their growth could proceed in certain favorable conditions (Xie & Zhou 2008, 2009), it would be significantly slowed, requiring a timescale of 10^7 years or even longer (Xie et al. 2010). This result raises a problem for the formation of a gaseous giant planet because it would not form a planetary core (via planetesimal growth) to accrete gas before the gas disk dissipation, which takes a timescale as short as 10^7–10^8 years for such close binaries (Cieza et al. 2009; Kraus et al. 2012). Following the above logic, Xie et al. (2010) found that Jupiter-like planets are unlikely to form around Alpha Centauri B. As for the case of HD 87646, the formation of the two massive substellar objects via the core accretion model would be more problematic because it requires a more massive disk with a mass larger than 68 M_{\text{Jup}}. Such a massive disk is seldom observed in close binaries, which indicates that such a massive disk exist, it would dissipate much faster than a normal lighter one.

Conversely, the disk instability model could circumvent most of the above barriers. First, disk instability usually requires a very high disk mass, which is in line with the masses of the two detected substellar objects. Second, planet formation via disk instability requires a short timescale, which is also consistent with the short disk dissipation timescale observed in close binaries. In addition, the model of disk instability is recently advocated by DUCHÊNE (2010), who argued that planet formation might be dominated by disk instability in close binaries based on the fact that exoplanets within close binaries (separation < 100 au) are significantly more massive than those within wide binaries or single stars. We could use the planet and BD mass to estimate the minimum surface density of the primordial disk, and test if such a disk is gravitationally unstable. We adopt the similarity solution of the evolving viscous disk (HARTMANN et al. 1998) where the surface density follows R^{-1} from the star to the disk edge. Since the binary separation is 19 au, the tidal truncation radius for the circumstellar disk around the primary star is ~6 au (1/3 of the binary separation). Spreading the total mass of the 12.4 + 57 Jupiter mass to this 6 au disk, the disk surface density at 6 au is 2604 g cm^{-2}. At 6 au, the temperature is around 90 K with 1 solar luminosity. The sound speed is 0.56 km s^{-1}. Then the Toomre Q parameter with a 1.12 solar mass star is 1.5. At 1 au, the temperature is around 220 K. The surface density is 15610 g cm^{-2}. The sound speed is 0.87 km s^{-1}. The Toomre Q parameter is 5.7. Considering the primordial disk mass should be a lot more massive than the planet and BD mass, the disk is likely to be gravitationally unstable throughout the disk. This is consistent with gravitational instability leading to planet formation. Although several advantages exist for the disk instability model, we consider that such an explanation for the formation of the HD 87646 system should be taken with caution because whether disk instability can be triggered in the present of a close stellar companion remains an issue under debate (NELSON 2000; MAYER et al. 2005; BOSS 2006).

Next, we want to discuss how the giant planet, b, moved to its current position with a very low eccentricity. Although the KOZAI-LIDOV mechanism and subsequent tidal dissipation (WU & MURRAY 2003; FABRYCKY & TREMAINE 2007) have often been invoked to explain the formation of hot Jupiters, it is unlikely that the BD, c, has helped to move b inward because such a process cannot help to form “warm” Jupiters (ANTONINI et al. 2016). Thus, we prefer a scenario in which b initially formed in the disk and then migrated inward in the disk to its current position, which explains why it has a near-zero eccentricity. As for the BD, c, after it formed in the disk, scattering between c and other objects formed in the disk moved it to a higher eccentricity. During such a scattering process, lower mass objects tend to be ejected out and more massive objects are kicked inward with a higher eccentricity according to the simulation of CHATTERJEE et al. (2008). The stellar companion, B, cannot excite the eccentricity of c because KOZAI oscillations will be destroyed by the presence of other massive substellar objects in the system (in this case, the giant planet b) according to the studies of WU & MURRAY (2003) and FABRYCKY & TREMAINE (2007). However, the presence of the stellar companion, B, can help to enhance the scattering process between c and other objects formed in the protoplanetary disk around A (MARZARI et al. 2005). Future astrometry observations, like those from Gaia (PERREYRAN et al. 2001), can provide a better binary orbital solution and even possibly constrain the BD candidate’s orbit. These data will help us study the dynamic structure of this complicated system and give more insight into its formation scenario.

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