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A PLANETARY COMPANION TO THE HYADES GIANT ϵ TAURI

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ABSTRACT

We report the detection of an extrasolar planet orbiting ϵ Tau, one of the giant stars in the Hyades open cluster. This is the first planet ever discovered in an open cluster. Precise Doppler measurements of this star from Okayama Astrophysical Observatory have revealed Keplerian velocity variations with an orbital period of 594.9 ± 5.3 days, a semiamplitude of 95.9 ± 1.8 m s^{-1}, and an eccentricity of 0.151 ± 0.023. The minimum mass of the companion is $7.6 \pm 0.2\ M_J$, and the semimajor axis is 1.93 ± 0.03 AU adopting a stellar mass of $2.7 \pm 0.1\ M_{\odot}$. The age of 625 Myr for the cluster sets the most secure upper limit ever on the timescale of giant planet formation. The mass of 2.7 $M_{\odot}$ for the host star is robustly determined by isochrone fitting, which makes the star the heaviest among planet-harboring stars. Putting together the fact that no planets have been found around about 100 low-mass dwarfs in the cluster, the frequency of massive planets is suggested to be higher around high-mass stars than around low-mass ones.

Subject headings: open clusters and associations: individual (Hyades) — planetary systems — stars: individual (ϵ Tauri) — techniques: radial velocities

1. INTRODUCTION

During the past decade, planet hunters have mainly observed thousands of nearby, field, and solar-type dwarfs by precise Doppler techniques, revealing about 200 extrasolar planets (e.g., Butler et al. 2006).[7] The planets exhibit a wide variety in their properties such as mass, semimajor axis, eccentricity, and multiplicity (e.g., Marcy et al. 2005). The distribution and correlation of these properties and the characteristics of their host stars (e.g., metallicity) now serve as the test cases for theorier of the formation and evolution of planetary systems around solar-type stars (e.g., Ida & Lin 2004; Fischer & Valenti 2005). In the past few years, targets of Doppler planet searches have included not only solar-type dwarfs but also various types of stars, such as evolved (sub)giants (Frink et al. 2002; Setiawan et al. 2005; Sato et al. 2005; Hatzes et al. 2005; Johnson et al. 2006) and early-type dwarfs (Galland et al. 2005). Planets around them have begun to show a further diversity in their properties, which are not necessarily the same as those of planets around solar-type stars (Hatzes et al. 2006).

Although the diversity of planets must reflect variety in the nature of their host stars and the history of formation and evolution of planetary systems, the precise relationship is still unclear, because it is difficult to determine even fundamental parameters of field stars, such as mass and age, and their birth environment. This makes it difficult to determine the dependences of planets on host stars' proprieties and arrange the planets on an evolutionary time series.

Open clusters provide ideal platforms to overcome this difficulty. They form homogeneous samples of stars with uniform initial chemical compositions and well-understood birth environments. In a cluster, the mass of the host star is the primary independent variable (Cochran et al. 2002). We can thus first derive the properties of planets as a function of stellar mass, and then, comparing them with those for other clusters, we can investigate their variation and evolution as a function of age, metallicity, etc. Radial velocity surveys, however, have not extensively targeted open clusters so far, mainly because of their faintness (typically $V > 10$ for dwarfs) for high-resolution spectroscopy, even when using 8–10 m class telescopes. The sole available result is from a survey conducted by Cochran et al. (2002), who monitored 98 F–M "dwarfs" in the Hyades open cluster, the closet one to the Sun, but found no planets around them (Paulson et al. 2004).

In this paper, we report the first discovery of an extrasolar planet in an open cluster: a planetary companion orbiting one of the Hyades "giants," ϵ Tau.

2. STELLAR PROPERTIES

The Hyades is the closest open cluster to the Sun (~45 pc) located in the constellation of Taurus. It contains about 400 coeval members aged 625 ± 50 Myr, as determined by isochrone fitting (Perryman et al. 1998), including four evolved giants (δ Tau, γ Tau, ϵ Tau, θ^1 Tau),[8] as well as numerous main-sequence stars with spectral types later than mid-A (less massive than ~2.4 $M_{\odot}$). Perryman et al. (1998) derived a mean metallicity for the Hyades of $[Fe/H] = 0.14 \pm 0.05$ from the compiled data of 40 Hyades stars, and Paulson et al. (2003) reported acluster mean $[Fe/H] = 0.13 \pm 0.01$ based on high-resolution spectra of F–K dwarfs.

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[7] See, e.g., the table at http://www.ciw.edu/boss/planets.html.

[8] δ Tau and θ^1 Tau are spectroscopic binaries with periods of about 530 days and 16 yr, respectively.

TABLE 1
Stellar Parameters for ϵ Tau

Parameter	Value
Spectral type	K0 III
π (mas)	21.04 ± 0.82
V	3.53
$B - V$	1.014
$T_{\rm eff}$ (K)	4901 ± 20
log g (cm s^{-2})	2.64 ± 0.07
v_t (km s^{-1})	1.49 ± 0.09
[Fe/H]	0.17 ± 0.04
R ($R_\odot$)	13.7 ± 0.6
L ($L_\odot$)	97 ± 8
M ($M_\odot$)	2.7 ± 0.1
$v \sin i$ (km s^{-1})	2.5

ϵ Tau (HR 1409, HD 28305, HIP 20889) is one of the high-fidelity members of the cluster based on parallax, proper motion, and radial velocity (Perryman et al. 1998; de Bruijne et al. 2001). The star is placed at a distance of 47.5 pc by the *Hipparcos* parallax (Perryman et al. 1997) of $\pi = 21.04 \pm 0.82$ mas and is classified in the catalog as a K0 III giant with a V magnitude $V = 3.53$ and a color index $B - V = 1.014$. *Hipparcos* made a total of 60 observations of the star over a time span of 2 yr, revealing a photometric stability down to $\sigma \sim 0.005$ mag.

We determined the atmospheric parameters and Fe abundance of ϵ Tau based on the spectroscopic approach using the equivalent widths of well-behaved Fe I and Fe II lines measured from our spectra taken without an iodine cell between 5000–7000 Å (see Takeda et al. 2002, 2005 for a detailed description of this method). We obtained an effective temperature $T_{\rm eff} = 4901 \pm 20$ K, a surface gravity $\log g = 2.64 \pm 0.07$ cm s^{-2}, a microturbulent velocity $v_t = 1.49 \pm 0.09$ km s^{-1}, and a metallicity $[{\rm Fe/H}] = 0.17 \pm 0.04$, which is consistent with the mean metallicity of the Hyades described above. Gray (1982) derived a projected rotational velocity of the star $v \sin i = 2.5$ km s^{-1}. Mozurkewich et al. (2003) measured an angular diameter of 2.671 ± 0.032 mas for the star by interferometry, which yielded the stellar radius $R = 13.7 \pm 0.6\ R_\odot$ combined with the *Hipparcos* distance. The luminosity for the star, $L = 97 \pm 8\ L_\odot$, was obtained from the effective temperature and stellar radius. We estimated the mass for the star as $M = 2.7 \pm 0.1\ M_\odot$ using these physical parameters and solar-metallicity isochrones (Girardi et al. 2000), which fit the locations of all four Hyades giants on the H-R diagram quite well as red clump giants. The mass for ϵ Tau corresponds to that for early A-type stars on the main sequence. A secure lower limit to the mass can be independently set by a mass of $2.42 \pm 0.30\ M_\odot$ for one of the Hyades turnoff stars, θ^2 Tau,[9] which is derived from the astrometric and spectroscopic orbital solutions (Torres et al. 1997). Stellar properties of ϵ Tau are summarized in Table 1.

Figure 1 shows Ca II H lines for γ Tau and ϵ Tau together with those for stars in our sample showing significant emissions in the line cores. Although the calibration to measure chromospheric activity for our spectra and the correlation between chromospheric activity and intrinsic radial velocity "jitter" for giants have not been well established yet, the lack of significant emission in the lines of γ Tau and ϵ Tau suggests that these stars are chromospherically inactive. Further discussions are presented in § 4.

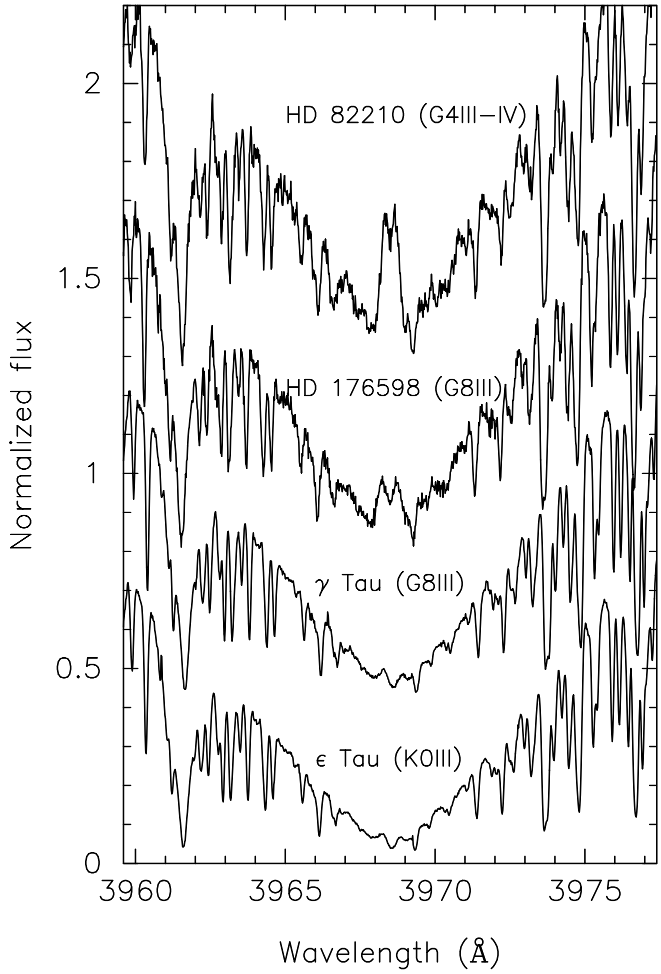

Fig. 1.—Spectra in the region of Ca II H lines. HD 82210 and HD 176598 show significant core reversals in the lines, suggesting high chromospheric activity. They have relatively large radial velocity scatters of $\sigma \sim 40$ m s^{-1}. γ Tau and ϵ Tau exhibit no emission in the lines.

3. RADIAL VELOCITY AND ORBITAL SOLUTION

All of the observations were carried out using High Dispersion Echelle Spectrograph (HIDES; Izumiura 1999) at Okayama Astrophysical Observatory (OAO) as part of our radial velocity survey of G and K giants to search for planets around intermediate-mass stars (Sato et al. 2005). For radial velocity measurements, a wave band of 5000–6100 Å was observed, and the slit width was set to 200 μm (0.76″), giving a wavelength resolution ($\lambda/\Delta\lambda$) of ~70000, where the resolution element is sampled by about 3.5 pixels. An iodine (I_2) absorption cell (Kambe et al. 2002) was used for precise wavelength calibration. The reduction of echelle data was performed using the IRAF[10] software package in a standard manner. Our modeling technique of an I_2-superposed stellar spectrum is detailed in Sato et al. (2002), giving a Doppler precision of about 6 m s^{-1} over a time span of 5 yr.

We collected a total of 20 radial velocity data of ϵ Tau between 2003 December and 2006 July, with a typical signal-to-noise ratio of 200 per pixel for an exposure time of less than a few minutes.

[9] θ^2 Tau is a proper-motion companion to θ^1 Tau and is itself a spectroscopic binary like θ^1 Tau. Torres et al. (1997) also derived a mass of $2.91 \pm 0.88\ M_\odot$ for θ^1 Tau using the astrometric and spectroscopic orbital solutions.

[10] 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.

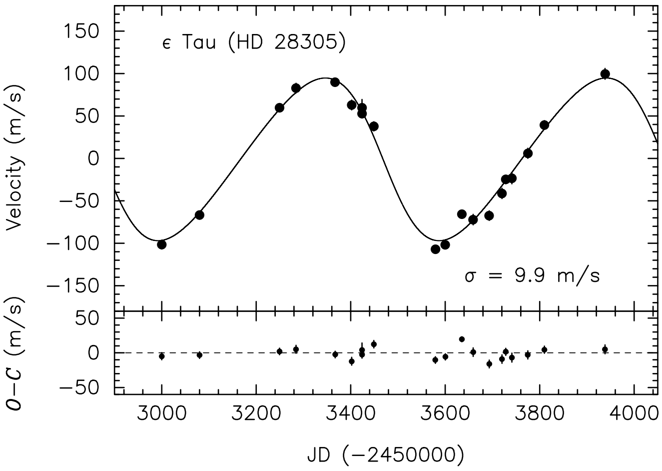

Fig. 2.— *Top*: Observed radial velocities of ϵ Tau (*dots*). The Keplerian orbital fit is shown by the solid line. *Bottom*: Residuals to the Keplerian fit. The rms to the fit is 9.9 m s^{-1}.

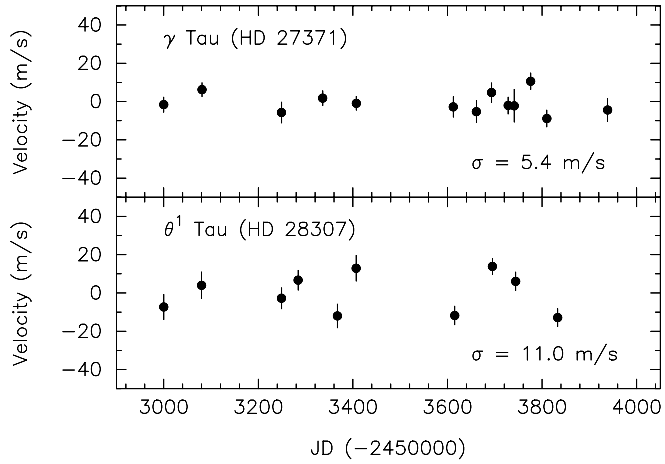

Fig. 3.—Observed radial velocities of γ Tau (*top*) and θ^1 Tau (*bottom*). θ^1 Tau is a spectroscopic binary having an orbital period of about 16 yr. The best-fit linear radial velocity trend with $\sim$830 m s^{-1} yr^{-1} has been subtracted in the figure. γ Tau is considered to be a single star. The rms scatter around a mean velocity is 5.4 m s^{-1} for γ Tau, and the rms scatter to the best-fit trend is 11.0 m s^{-1} for θ^1 Tau.

The observed radial velocities are shown in Figure 2 and are listed in Table 2 together with their estimated uncertainties. The measurement error of each observation is derived from an ensemble of velocities from each of $\sim$200 spectral regions (each 5 Å long) in every exposure. We also observed γ Tau and θ^1 Tau almost every time when ϵ Tau was observed. As shown in Figure 3, both of the stars have small radial velocity scatters of $\sigma = 5.4$ and 11.0 m s^{-1} (scatters around the linear trend for θ^1 Tau), respectively. This level of scatters is typical for late G- to early K-type giants (Sato et al. 2005).

The observed radial velocities for ϵ Tau can be well fitted by a Keplerian orbit with a period $P = 594.9 \pm 5.3$ days, a velocity semiamplitude $K_1 = 95.8 \pm 1.8$ m s^{-1}, and an eccentricity $e = 0.151 \pm 0.023$. The resulting model is shown in Figure 2, and its parameters are listed in Table 3. The uncertainty of each parameter was estimated using a Monte Carlo approach. The rms scatter of the residuals to the Keplerian fit was 9.9 m s^{-1}, which is comparable to the scatters of γ Tau and θ^1 Tau, suggesting that ϵ Tau is also intrinsically stable in radial velocity. If we assume that the observed radial velocity variability is due to an orbital motion, we obtain a minimum mass for the companion of $m_2 \sin i = 7.6 \pm 0.2\ M_J$ and a semimajor axis of $a = 1.93 \pm 0.03$ AU. The uncertainties mostly come from the host star's mass. The average value of $\sin i$ for randomly oriented orbits, $\pi/4$, gives a mass for the companion of 9.7 M_J, which still falls within the planetary-mass regime. The companion thus becomes the first planet ever discovered in an open cluster.

TABLE 2
Radial Velocities for ϵ Tau

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
3000.0817	−101.5	5.2
3080.0119	−66.8	4.7
3249.2986	59.9	4.8
3284.2648	82.8	5.7
3367.1614	89.7	4.7
3402.0266	62.9	5.7
3423.9447	59.6	9.9
3423.9618	52.6	5.0
3449.0016	37.7	5.4
3579.3094	−107.0	4.8
3600.2646	−101.8	4.4
3635.3287	−65.7	3.5
3659.2297	−72.1	6.2
3693.3002	−67.4	5.6
3720.1975	−41.2	6.1
3728.2251	−24.7	5.1
3741.1005	−23.5	6.5
3774.9119	6.0	5.9
3809.9800	39.3	5.2
3938.3112	99.7	6.4

4. LINE SHAPE ANALYSIS

Although the radial velocity variability in ϵ Tau can be plausibly explained by an orbital motion, intrinsic phenomena on the stellar surface, such as rotational modulations in chromospheric active stars and pulsations, may produce similar periodic radial velocity variations. However, ϵ Tau is probably chromospherically inactive, because we found no significant emission in the Ca ii H and K line cores, as shown in Figure 1. Moreover, the rotational period estimated by the projected rotational velocity and the stellar radius is $P_{rot} \leq 2\pi R/v \sin i \sim 280$ days (R is a stellar radius), which is incompatible with the observed period. If the rotational velocity contained a large error, and observed period were the same as the rotational period, giving a rotational

TABLE 3
Orbital Parameters for ϵ Tau

Parameter	Value
P (days)	594.9 ± 5.3
K_1 (m s^{-1})	95.9 ± 1.8
e	0.151 ± 0.023
ω (deg)	94.4 ± 7.4
T_p (JD−2,450,000)	2879 ± 12
$a_1 \sin i$ (10^{-3}AU)	5.192 ± 0.097
$f_1(m)$ ($10^{-8}\ M_{\odot}$)	5.27 ± 0.28
$m_2 \sin i$ (M_J)	7.6 ± 0.2
a (AU)	1.93 ± 0.03
N_{obs}	20
rms (m s^{-1})	9.9
Reduced χ^2	4.5

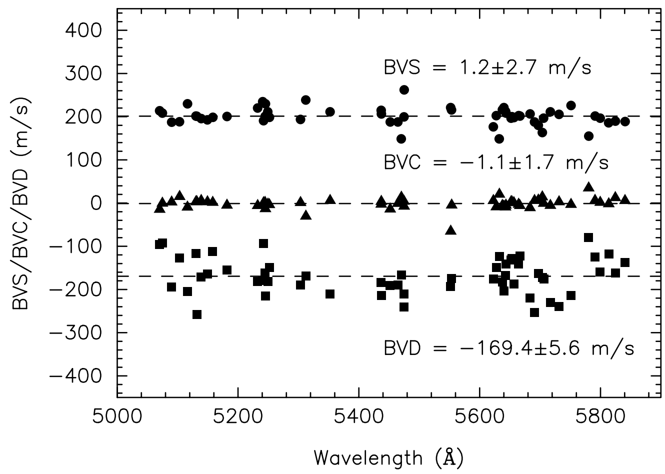

FIG. 4.—Bisector quantities of cross-correlation profiles between the templates of ϵ Tau at peak (70–100 m s^{-1}) and valley (−100 to −70 m s^{-1}) phases of observed radial velocities, showing bisector velocity span (BVS, *circles*), bisector velocity curvature (BVC, *triangles*), and bisector velocity displacement (BVD, *squares*). The definition of these quantities are described in § 4. The mean values and their standard errors are shown in the figure. Dashed lines represent mean values of the quantities (an offset of 200 m s^{-1} is added to the BVS).

velocity of 1.2 km s^{-1}, the observed velocity amplitude of about 100 m s^{-1} would require a spot covering about 8% of the stellar disk, which should also produce photometric variation by a factor of 0.08 mag, whereas *Hipparcos* measurements show that the photometric stability of this star is $\sigma \sim 0.005$ mag. It is thus unlikely that rotational modulation is the cause of the variability. The radial pulsation hypothesis is also ruled out by the 595 day period, because the timescale of the fundamental mode for ϵ Tau is expected to be only 1–2 days (Cox et al. 1972). Nonradial pulsations in gravity mode (g-mode) with longer periods might be possible, but such modes in giant stars should theoretically have a large amplitude not in the deep outer convective envelope but in the stellar radiative interior only. The fact that the two other Hyades giants (γ Tau and θ^1 Tau) we observed have nearly identical physical parameters but do not show significant radial velocity variations like ϵ Tau does not favor the pulsation hypothesis either.

One effective technique to distinguish between the planetary hypothesis and the others is to examine variations of spectral line shapes via line bisectors (e.g., Queloz et al. 2001). Orbital motion causes a shift of spectral lines as a whole, keeping line bisectors constant, while rotational modulation and pulsation cause a change in the shape of line bisectors. We analyzed line bisectors of the cross-correlation profile between stellar templates, which are normally used for our radial velocity analysis. Using our technique we can extract a high-resolution iodine-free stellar template from several stellar spectra contaminated by iodine lines (Sato et al. 2002). For the bisector analysis of ϵ Tau, we extracted two stellar templates: one was from five spectra with observed radial velocities of 70–100 m s^{-1} (template 1), and the other was from those with −100 to −70 m s^{-1} (Template 2). Each stellar template thus obtained holds the shape of spectral lines at the peak and valley phases of observed radial velocities, respectively. Then, if the radial velocity variations are due to orbital motion, the cross-correlation profile of template 1 relative to template 2 is expected to be symmetric having a peak at a velocity of −200 to −140 m s^{-1}. We calculated the cross-correlation profiles of the templates for 56 spectral segments (4–5 Å width each) in which severely blended lines or broad lines are not included, and the typical FWHM of the profiles is about 10 km s^{-1}. Three bisector quantities were calculated for the cross-correlation profile of each segment: the velocity span (BVS), which is the velocity difference between two flux levels of the bisector; the velocity curvature (BVC), which is the difference of the velocity span of the upper half and lower half of the bisector; and the velocity displacement (BVD), which is the average of the bisector at three different flux levels. We used flux levels of 25%, 50%, and 75% of the cross-correlation profile to calculate the above quantities. Figure 4 shows the resulting bisector quantities plotted against the center wavelength of each segment. As expected from the planetary hypothesis, both the bisector velocity span and the curvature are identical to zero (1.2 m s^{-1} and −1.1 m s^{-1} on average, respectively), which means that the cross-correlation profiles are symmetric, and the average bisector velocity displacement of −169.4 m s^{-1} is consistent with the velocity difference between the two templates. Furthermore, these values are irrelevant to wavelength. Based on these results, we conclude that a planetary hypothesis is the most viable explanation for the radial velocity variability observed in ϵ Tau.

5. DISCUSSION

Our discovery clearly shows that a massive planet up to 7.6 ± 0.2 M_J can form around a 2.7 ± 0.1 $M_\odot$ star within 625 ± 25 Myr. This timescale is the most secure upper limit ever set on giant planet formation, because uncertainty in the age of field stars is typically on the order of Gyr. The planet directly provides a constraint on the timescale of giant planet formation independent of observations of protoplanetary disks around young stars (Haisch et al. 2001a, 2001b). The existence (or absence) of planets in further younger clusters can set a more stringent upper limit on it. The stellar mass of 2.7 $M_\odot$ is robustly determined, and it makes the star the heaviest among planet-harboring stars with reliable initial masses, as field planet-harboring G and K giants, which are suspected to be more massive than 2 $M_\odot$ have large uncertainty in their masses (Setiawan et al. 2003, 2005; Sato et al. 2003; Hatzes et al. 2005). The discovery demonstrates that G and K giants in open clusters are the most appropriate for planet searches around massive stars by radial velocity techniques, while those on the main sequence are unsuitable for this purpose because of the lack of absorption lines in their spectra.

How did the planet form around ϵ Tau? In the standard core-accretion scenario with a minimum mass ($\sim$0.01 $M_\odot$) solar nebula (e.g., Pollack et al. 1996), a giant planet only forms beyond the "snow line" ($\sim$2.7 AU), where plenty of ice is available to form a massive solid core capable of acquiring a huge gas envelope. In the case of a 2.7 $M_\odot$ star, however, the snow line is pushed out to $\sim$20 AU because of its strong radiation ($\sim$50 $L_\odot$), which is then probably too far for a planet to form within about 600 Myr. A massive protoplanetary disk ($\sim$0.1 $M_\odot$ and more), as found around some young Herbig Ae/Be stars (Natta et al. 2000), may have produced the heavy planet around ϵ Tau. Although effects of radiation from the central hot star need to be investigated more extensively, a large core can rapidly form without the help of ice, even at $\lesssim$20 AU in such massive disks (Kokubo & Ida. 2002; Ida & Lin 2005). The recent model, including core growth during migration (Alibert et al. 2005), may be an alternative scenario in which disk mass needs not be significantly large. On the other hand, the disk instability model (e.g., Boss 2005), a competing scenario to the core-accretion scenario, can form massive planets within thousands of years. Theoretical studies of planet formation around massive stars, together with improved statistics on disks and planets around them, are highly encouraged. Another convenient way to host a massive planet without infringing upon the above constraints is to capture the planet by a stellar encounter. But that may be ruled out in our case. The stellar encounter hypothesis generally prefers a highly eccentric orbit, while $e = 0.15$ was found here. The timescale of about 600 Myr is too short for the tidal force from the host star to nearly circularize such a orbit at a distance of 1.93 AU.

This discovery enables us for the first time to investigate properties of giant planets as a function of host star's mass for a homogeneous sample in terms of stellar metallicity and birth environment. The frequency of a massive planet with $\gtrsim 5\ M_J$ is currently estimated to be about 1% for field FGK stars (e.g., Marcy et al. 2005) and much smaller than 1% for M stars (e.g., Butler et al. 2004). Assuming the same frequency for the Hyades dwarfs and the three massive giants we observed, the probability that the previous survey that comprised 78 FGK stars and 20 M stars found no planets (Cochran et al. 2002; Paulson et al. 2004) but the one we found is only $(0.99)^{78}(0.99 \times 0.99 \times 0.01 \times 3) = 0.013$. This small probability may suggest that massive giant planets are more abundant around high-mass stars than around low-mass ones. On the basis of the core-accretion scenario, such massive planets possibly tend to form around massive stars, because they can possess more massive disks than low-mass stars can. The disk instability model generally prefers massive planets to low-mass ones, but the mass distribution and frequency of planets should not strongly depend on stellar mass, because the critical parameter in this scenario is the disk-to-steller mass ratio. A census of planets around other massive stars in the cluster, including early-type dwarfs and white dwarfs (Friedrich et al. 2005), will help discriminate between these scenarios.

ϵ Tau is regarded as a red clump giant (RCG) in the cluster, that is, a core-helium burning star. If it is indeed a RCG, the planet survived the phase of the tip of the red giant branch (RGB), where the stellar radius should have reached $\sim 40\ R_{\odot}$ (0.2 AU) without being engulfed in the central star by the tidal force. The orbital radius dividing the life and death of planets during the RGB phase depends highly on the stellar radius and internal structure, such as the depth of the convective envelope. Around a 2.7 $M_{\odot}$ star, the boundary probably lies at $\sim$0.8 AU (Zahn 1989). Examining the distribution of the orbital radius of such inner planets around giants would improve the stellar evolutionary model.

Well-determined ages of open clusters enable us to trace the evolution of planets and life. For example, at age 600 Myr, which corresponds to that of Hyades, oceans and the first primitive life forms appeared on the Earth. Habitable zones around early-type stars are about 10 AU corresponding to an angular separation of 0.2″ at the distance of Hyades, and those around solar-type stars are at 0.02″ ($\sim$1 AU). Earth-like planets in these habitable zones can be good targets for future space coronagraphy and interferometry missions. Nearby open clusters with well-determined ages may provide us live candidates for quests for life.

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