

## A PLANETARY-MASS COMPANION TO THE K0 GIANT HD 17092

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### ABSTRACT

We report the discovery of a substellar-mass companion to the K0 giant HD 17092 with the Hobby-Eberly Telescope. In the absence of any correlation of the observed 360 day periodicity with the standard indicators of stellar activity, the observed radial velocity variations are most plausibly explained in terms of a Keplerian motion of a planetary-mass body around the star. As the estimated stellar mass is  $2.3 M_{\odot}$ , the minimum mass of the planet is  $4.6 M_J$ . The planet's orbit is characterized by a mild eccentricity of  $e = 0.17$  and a semimajor axis of 1.3 AU. This is the tenth published detection of a planetary companion around a red giant star. Such discoveries add to our understanding of planet formation around intermediate-mass stars, and they provide dynamical information on the evolution of planetary systems around post-main-sequence stars.

*Subject headings:* planetary systems — stars: individual (HD 17092)

### 1. INTRODUCTION

After more than a decade of discovering planets around Sun-like stars, it has become apparent that to achieve a satisfying level of understanding of planet formation and evolution, surveys have to be extended to other types of stars. So far, the most successful of these have been searches for planets around low-mass dwarfs, which have been driven by, among other goals, the anticipation that Earth-mass planets can be found in their habitable zones (Marcy et al. 2005; Mayor et al. 2005). Surveys of white dwarfs, which probe their ancient planetary systems, the survivors of the evolution of their parent stars, exemplify an extension of planet searches to the endpoint of stellar evolution (e.g., Kepler et al. 2005). Finally, searches for neutron star planets can provide information on planets around massive stars (Thorsett & Dewey 1993) and on planet formation in extreme, post-supernova environments (Konacki & Wolszczan 2003; Wang et al. 2006).

Yet another, so far meagerly explored area of extrasolar planetary research involves searches for planets around giant stars. More than a decade ago, precision radial velocity (RV) studies established that GK giant stars exhibit RV variations ranging from days to many hundreds of days (e.g., Walker et al. 1989; Hatzes & Cochran 1993, 1994). Enough observational evidence has been accumulated to identify three distinct sources of this variability: stellar pulsations, surface activity, and the presence of substellar companions. Since Doppler searches for planets around main-sequence (MS) stars become inefficient for spectral types earlier than F6–F8, because of a paucity of spectral features and their rotational broadening, extending studies of planetary system formation and evolution to stellar masses substantially larger than  $1 M_{\odot}$  is observationally difficult. A potentially very efficient, indirect way

to remove this difficulty is to conduct surveys of post-MS giants. These evolved stars have cool atmospheres and many narrow spectral lines that can be utilized in RV measurements to give an adequate precision level ( $<10 \text{ m s}^{-1}$ ). Discoveries of planets around post-MS giants, in numbers comparable to the current statistics of planets around MS-dwarfs (e.g., Butler et al. 2006), will most certainly provide much needed information on planet formation around intermediate-mass MS progenitors ( $\geq 1.5 M_{\odot}$ ), and they will create an experimental basis with which to study the dynamics of planetary systems orbiting evolving stars (e.g., Duncan & Lissauer 1998). Sufficiently large surveys of post-MS giants should furnish enough planet detections to meaningfully address the problem of the long-term survival of planetary systems around stars that are off the MS and on their way to the final white dwarf stage.

In order to address the above issues, we have joined the existing surveys (e.g., Hatzes et al. 2006; Sato et al. 2007 and references therein) with our own long-term project to search for planets around evolved stars with the 9.2 m Hobby-Eberly Telescope and its High-Resolution Spectrograph. The sample of stars we have been monitoring since early 2004 is composed of two groups, approximately equal in number. The first group falls in the “clump giant” region of the HR-diagram (Jimenez et al. 1998), which contains stars of various masses over a range of evolutionary stages. The second group comprises stars that have recently left the MS and are located  $\sim 1.5$  mag above it. Generally, all our targets, a total of  $>900$  GK giants brighter than  $\sim 11$  mag, occupy the area in the HR-diagram approximately defined by the MS, the instability strip, and the coronal dividing line (a narrow strip in the HR-diagram marking the transition between stars with steady hot coronae and those with cool chromospheric winds; Linsky & Haisch 1979). If the frequency of occurrence of planets around MS-progenitors of GK giants is similar to that of planets around solar-type stars, our survey should detect 50–100 planets and planetary systems, which, together with the detections from similar projects, will provide a firm basis for studies of planetary system formation and evolution around  $>1 M_{\odot}$  stars.

In this paper, we describe our survey and the detection of a planetary-mass companion to the K0 giant HD 17092. Details of the observing procedure and survey strategy are given in § 2, followed by a description of the basic properties of HD 17092 in § 3.

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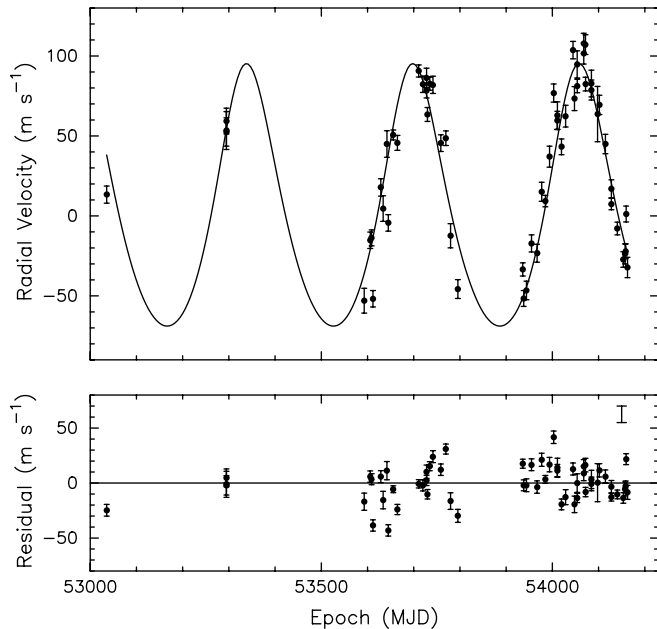


FIG. 1.— *Top*: Radial velocities (*filled circles*) and the best-fit orbit (*solid line*) for HD 17092. *Bottom*: Residuals from the best-fit of a Keplerian orbit to data. The vertical bar indicates an additional error added in quadrature to the formal uncertainties of radial velocity measurements.

The analysis of radial velocity and line bisector measurements, including a discussion of the *Hipparcos* photometry of the star, is given in § 4. Finally, our results are discussed and summarized in § 5.

## 2. OBSERVATIONS

Observations were made between 2004 January and 2007 March, with the Hobby-Eberly Telescope (HET) (Ramsey et al. 1998) equipped with the High-Resolution Spectrograph (HRS) (Tull 1998) in the queue-scheduled mode (Shetrone et al. 2007). The spectrograph was used in the  $R = 60,000$  resolution mode with a gas cell ( $I_2$ ) inserted into the optical path, and it was fed with a  $2''$  fiber. The observing scheme followed standard practices implemented in precision radial velocity measurements with the iodine cell (Marcy & Butler 1992). The spectra consisted of 46 echelle orders recorded on the blue CCD chip (407.6–592 nm) and 24 orders on the red one (602–783.8 nm). The spectral data used for RV measurements were extracted from the 17 orders, which cover the 505–592 nm range of the  $I_2$  cell spectrum.

Originally, HD 17092 was observed as part of the astrometric reference star selection program related to a search for terrestrial-mass planets with the *Space Interferometry Mission* (Gelino et al. 2005; Niedzielski et al. 2005). The star was added to the list of candidates for substellar companions when it became clear that it exhibited RV variations, which disqualified it as a potential astrometric reference standard.

The observing strategy is illustrated in Figure 1. Measurements of a particular target star begin with 2–3 exposures, typically 3–6 months apart, to check for any RV variability exceeding a  $30\text{--}50\text{ m s}^{-1}$  threshold. If a significant variability is detected, the star is scheduled for more frequent observations, and, if the RV variability is confirmed, it becomes part of the high-priority list.

We have collected radial velocity measurements of HD 17092 at 59 epochs. Typically, the signal-to-noise ratio per resolution element in the spectra was 200–250 at 594 nm in 3–8 minutes, depending on the atmospheric conditions. The basic data reduction

TABLE 1  
STELLAR PARAMETERS OF HD 17092

Parameter	Value
$V$ .....	7.73
$B-V$ .....	$1.247 \pm 0.014$
Spectral type .....	K0 III
$T_{\text{eff}}$ .....	$4650 \pm 35$
$\log g$ .....	$3.0 \pm 0.12$
[Fe/H] .....	$0.22 \pm 0.08$
$M_*$ .....	$2.3 \pm 0.3 M_{\odot}$

was performed using standard IRAF<sup>7</sup> scripts. Radial velocities were measured by means of the commonly used  $I_2$  cell calibration technique (Butler et al. 1996). A template spectrum was constructed from a high-resolution Fourier transform spectrometer (FTS)  $I_2$  spectrum and a high signal-to-noise stellar spectrum measured without the  $I_2$  cell. Doppler shifts were derived from least-square fits of template spectra to stellar spectra with the imprinted  $I_2$  absorption lines. The resulting radial velocity measurement for each epoch was derived as a mean value of the independent determinations from the 17 usable echelle orders. The corresponding uncertainties of these measurements were calculated assuming that errors obeyed the Student's  $t$ -distribution, and they typically fell in a  $4\text{--}5\text{ m s}^{-1}$  range at a  $1\sigma$  level. Radial velocities were referred to the solar system barycenter using the Stumpff (1980) algorithm.

## 3. THE STAR

HD 17092 (BD +49 767; Table 1) was classified as a K0 star by Cannon & Pickering (1924). These authors also measured its photographic and photovisual magnitudes to be  $P_{\text{tg}} = 8.8$  and  $P_{\text{tm}} = 7.8$  mag, respectively. The Tycho-2 catalog (Hog et al. 2000) lists the values of  $B_{\text{T}} = 9.374 \pm 0.019$  and  $V_{\text{T}} = 7.875 \pm 0.011$  mag derived from the *Hipparcos* observations of the star. In the Tycho-1 catalog (Perryman et al. 1997), values of  $V = 7.73$  and  $B - V = 1.247 \pm 0.014$  mag are also given. In the Tycho star mapper experiment, a trigonometric parallax of HD 17092 was measured as  $9.2 \pm 5.5$  mas.

A detailed inspection of our spectra in the range of 515–520 nm (comparison of intensities and widths of Mg  $i$  b triplet lines at 516.7, 517.2, and 518.4 nm) suggests that the star is a giant. The absolute visual magnitude of HD 17092 is  $M_V = 1.76$  mag, assuming  $(B - V)_0 = 1.00$  mag after Schmidt-Kaler (1982), the above Tycho parallax, and  $R = 3.1$ . This makes the star almost 1 mag fainter than a typical  $M_V$  (K0 III) = 0.8 mag (Schmidt-Kaler 1982). In what follows, we will assume that HD 17092 is a typical giant with  $M_V = 0.8$  mag, as this value remains consistent with the Tycho parallax uncertainty.

The atmospheric parameters of HD 17092 were recently estimated by P. Zielinski & A. Niedzielski (2007, in preparation) through the analysis of 230 Fe I and 11 Fe II lines in the optical spectra. The results,  $T_{\text{eff}} = 4650$  K,  $\log g = 3.0$ , and  $[\text{Fe}/\text{H}] = 0.22$ , are very close to rough estimates obtained from the calibrations by Straizys & Kuriliene (1981), which give  $\log T_{\text{eff}} = 3.681$  and  $\log g = 2.89$ . P. Zielinski & A. Niedzielski (2007, in preparation) have also estimated the mass of HD 17092 as  $M = 2.3 \pm 0.3 M_{\odot}$  by comparing the star's position in the HR diagram with evolutionary tracks of Girardi et al. (2000), given the above metallicity. In absence of a direct measurement of the radius of

<sup>7</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 2  
MEASURED AND DERIVED ORBITAL PARAMETERS OF HD 17092b

Parameter	Value
$P$ (days).....	$359.9 \pm 2.4$
$T_0$ (MJD).....	$52969.5 \pm 12.3$
$K$ ( $\text{m s}^{-1}$ ).....	$82.4 \pm 3.2$
$a_1 \sin i$ (AU).....	$0.0027 \pm 0.0002$
$e$ .....	$0.166 \pm 0.052$
$\omega$ (deg).....	$347.4 \pm 13.4$
$f(m)$ ( $M_\odot$ ).....	$2.001 \times 10^{-8} \pm 1.1 \times 10^{-9}$
$m_2 \sin i$ ( $M_J$ ).....	$4.6 \pm 0.3$
$a_2$ (AU).....	$1.29 \pm 0.05$

HD 17092, we assume that it is similar to the radii of stars with  $[\text{Fe}/\text{H}] \geq -0.5$ , and adopt  $R = 10.9 \pm 2.8 R_\odot$  after Alonso et al. (2000).

The projected rotational velocity of HD 17092,  $v \sin i \leq 1 \text{ km s}^{-1}$ , was estimated using the cross-correlation method (Benz & Mayor 1984). From this value and the adopted stellar radius, we have obtained an estimate of the rotation period of HD 17092,  $P_{\text{rot}} \approx 551$  days. This value appears to be typical for K0 giants (de Medeiros et al. 1996). Given the error estimates of Alonso et al. (2000), the rotation period of HD 17092 may range from 409 to 692 days, which makes it significantly longer than the observed 360 day period of radial velocity variation.

#### 4. DATA ANALYSIS

##### 4.1. Modeling of the Companion Orbit

Radial velocity variations of HD 17092 over a 3 year period are shown in Figure 1, together with the best-fit model of a Keplerian orbit. The best-fit parameters of the orbit and their Monte Carlo estimated uncertainties are listed in Table 2. The phase origin of the model orbit coincides with the best-fit time of periastron passage,  $T_0$ . The residuals shown in Figure 1b are characterized by the rms value of  $\sim 16 \text{ m s}^{-1}$ . If the observed RV variations are indeed caused by an orbiting companion, it moves in a  $\sim 360$  day, moderately eccentric orbit, with a semimajor axis of 1.3 AU, and has a minimum mass of  $m_2 \sin i = 4.6 M_J$  for the assumed stellar mass of  $2.3 M_\odot$ . This mass indicates a planetary origin of the object over a range of possible values of  $\sin i$  extending beyond the median inclination of  $i = 60^\circ$  for randomly oriented orbits. The reduced  $\chi^2 = 10$  for the fit suggests a presence of additional variations in the data, which have also been reported for other planet detections around giants (e.g., Frink et al. 2002), and are not uncommon for this type of stars (Setiawan et al. 2004; Hatzes et al. 2005). Our work also confirms that red giants exhibit a RV scatter at an average level of  $\sim 20 \text{ m s}^{-1}$ , as the result of a stochastic intrinsic stellar activity (Niedzielski & Wolszczan 2007). To account for these variations, we have adopted a conservative error estimation procedure by adding in quadrature a constant  $15 \text{ m s}^{-1}$  error to the RV measurement uncertainties, before performing a least-squares fit of the orbit. This approach resulted in parameter error estimates (Table 2) that realistically absorb any leftover, unmodeled RV variations in the data. Their nature will be further discussed when more data become available.

##### 4.2. Line Bisector and Curvature Analysis

Precision radial velocity measurements may be significantly affected by phenomena that are not related to stellar reflex motion caused by the presence of an orbiting planet. Changes in line shapes arising from motions in the stellar atmosphere, related to nonradial pulsations or inhomogeneous convection and/or spots

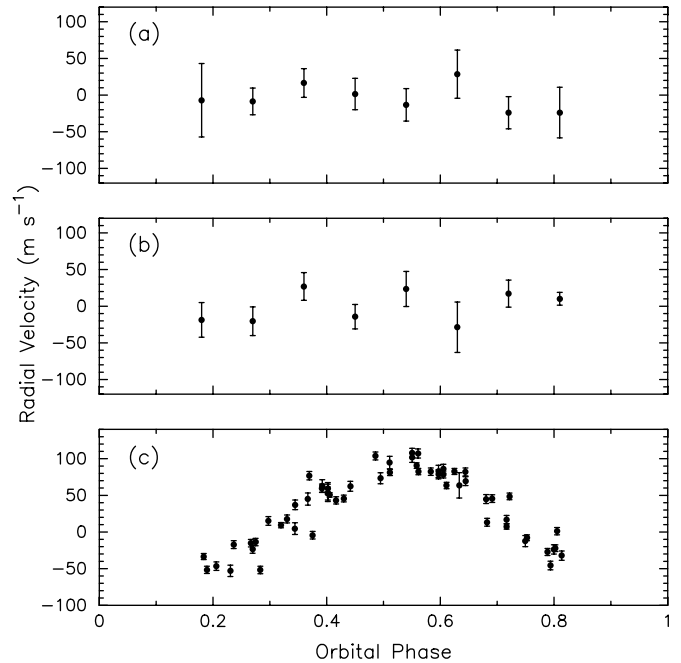


Fig. 2.—(a) Mean bisector velocity span and (b) curvature of HD 17092, binned as a function of orbital phase at the 0.1 interval, and compared to (c) the measured radial velocities of the star.

combined with rotation, or distortions induced by light contamination by an unseen stellar companion, can mimic low-level radial velocity variations. Therefore, especially in the case of giant stars, it is important to verify whether the observed radial velocity variations are real, or if they are possibly generated by changes in the symmetry of spectral lines due to the above effects.

The basic tool for studying the origin of RV variations derived from stellar spectra is the analysis of shapes of the spectral lines using the line bisector technique (Gray 1983, 2005). It has been extensively used in the process of confirming the planetary origin of RV variations in solar-type stars (Hatzes et al. 1997, 1998a, 1998b), and it has become a mandatory part of the analysis of RV data from giants (Setiawan et al. 2003, 2005; Hatzes et al. 2005; Reffert et al. 2006; Sato et al. 2007). To examine line profile variations in HD 17092, we selected several lines of a moderate intensity that were free of blends and were located close to the centers of echelle orders. Because the HRS spectra extend far beyond the range occupied by the  $I_2$  lines, we were able to measure line profiles in the same spectra used for radial velocity determination.

In order to avoid any contamination by the  $I_2$  spectrum, we selected lines in the wavelength range redward of 660 nm, which also meant that we could not use the standard bisector line of Fe I at 625.256 nm. Instead, we used three lines, Ni I 664.638 nm, Ni I 676.784 nm, and Cr I 663.003 nm, which were analyzed in detail to search for any possible systematic effects. In fact, Dall et al. (2006) found that the Ni I 664.3683 nm line shows larger bisector variations than the Fe I 625.256 nm line. The other two lines adopted for this analysis also show well-defined bisectors. We measured two line parameters, the line bisector span and its curvature, under the assumption that the mean bisector and velocity span of the three lines reflect the upper limit of possible atmospheric activity of the star. Uncertainties in the derived values of the bisector span and curvature were estimated as standard deviations from the mean.

The bisector span and curvature do not depart significantly from zero in Figure 2. Also note that, because of the proximity of the orbital period to 1 yr, the 0.38 gap in phase coverage will take a long time to fill.

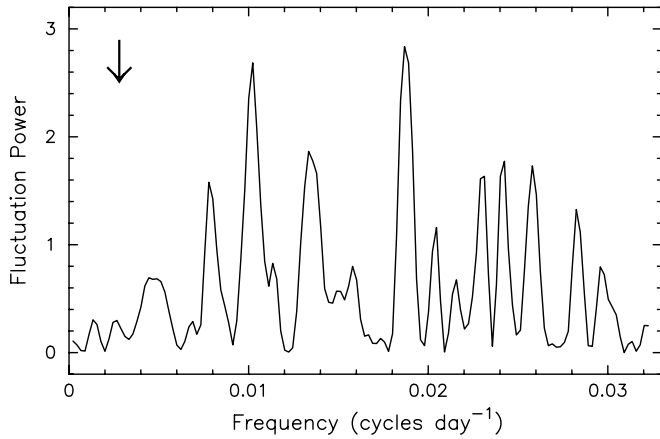


FIG. 3.—Periodogram of the *Hipparcos* photometric measurements of HD 17092. The vertical arrow marks the frequency corresponding to the 360 day period of the observed radial velocity variations.

#### 4.3. Photometric Variability

The *Hipparcos* star mapper (Tycho) made 124 photometric observations of HD 17092 in  $V_T$  and  $B_T$  between JD 2,447,915.85944 and 2,449,039.86213, about 12 yr before the beginning of our survey. The measured scatter in  $V_T$  was 0.092 mag without any sign of systematic variability (Perryman et al. 1997). The observed scatter is consistent with the precision of Tycho photometry for a given stellar magnitude range.

We performed a deeper search for any possible periodicities in the Tycho photometry of the star by computing a Lomb-Scargle periodogram of these data. None of the peaks in Figure 3 exceeds the false-positive probability of 0.5. In particular, no excess fluctuation power is present at and around the 360 day period detected in the RV data.

### 5. DISCUSSION AND CONCLUSIONS

In this paper, we have presented compelling evidence that the K0 giant, HD 17092, exhibits a strictly periodic radial velocity variation with a period of  $360 \pm 2$  days over a 1200 day span of observations. When interpreted in terms of a Keplerian motion, this periodicity indicates the presence of a substellar companion with a minimum mass of  $4.6 M_J$ , in a moderately eccentric orbit ( $e = 0.17 \pm 0.05$ ), 1.3 AU away from the star. As the long-period RV variations in red giants may also be related to a combination of effects including stellar rotation, activity, and nonradial pulsations (e.g., Hatzes et al. 2006), we have analyzed the photometric data and the behavior of line bisectors of the star, following the established practice (Queloz et al. 2001).

The magnitude of a star's photometric variability is related to the fraction of its surface covered by spots. The Tycho photometry, although not very precise, gives an upper limit to this variation of 0.011 mag in  $V_T$ , which translates to  $\sim 1\%$  of the stellar surface covered by spots. As discussed by Hatzes (2002), with this spot coverage and the star's rotational velocity of  $\sim 1$  km  $s^{-1}$ , it is impossible to produce RV variations of the observed amplitude. In fact, their maximum amplitude would be on the order of a few  $m s^{-1}$ , which is comparable to the precision of our RV measurements.

Hatzes (2002) has published estimates of the bisector velocity span (BVS) as a function of  $v \sin i$  and fraction of spots. For HD 17092, we derive from their formula a BVS of a few  $m s^{-1}$ , which is consistent with our own BVS determination. A detailed analysis of both line bisectors and bisector velocity span shows that there is no relationship between line profile variability and the

observed RV changes. In addition, line profile variations, measured with the same spectra as the ones used to obtain RVs, show no significant variation with phase.

A lack of both line profile variations and photometric variability eliminates nonradial pulsations and surface activity related to stellar rotation as possible causes of the observed RV variations in HD 17092. Another argument against a rotation-forced RV variation is the repeatability of the observed RV changes and their strictly periodic character. Spots, as we understand them, appear and disappear on the stellar surface, and the number of spots, as well as their locations, vary from one cycle to another. Therefore, a resulting variability is unlikely to maintain the same pattern over many cycles. In the case of HD 17092, the observed 3 cycles of the 360 day period are consistently fitted with a single Keplerian orbit. Consequently, the most plausible explanation of our data is the presence of a substellar-mass companion around the star.

A sufficiently large number of planet detections by high-precision RV surveys of GK giants will make them efficient tools with which to study planet formation around intermediate-mass stars and the dynamical evolution of planets induced by a post-MS evolution of their parent stars. Current constraints on stellar mass dependence on the disk mass and the timescale of depletion of its gas and dust components come from studies of disks around young stars. For example, in addition to the previous work (e.g., Haisch et al. 2001), recent *Spitzer* observations (e.g., Carpenter et al. 2006) appear to confirm that disks around intermediate- and high-mass stars have lifetimes significantly shorter than 5 Myr. These results have direct consequences for the competing theories of giant planet formation, because the core accumulation scenarios (Pollack et al. 1996; Wuchterl et al. 2000; Alibert et al. 2004) require at least a few million years for a core to form, whereas planet formation from a disk instability (Boss 1997; Mayer et al. 2002) can require much less. Clearly, the searches for planets around giant stars have a unique capability to provide the statistics needed to decisively constrain the efficiency of planet formation as a function of stellar mass and chemical composition.

It is quite reasonable to expect that the giant star surveys will have the potential to verify predictions of the post-MS orbital evolution that emerge from numerical simulations (e.g., Rasio & Ford 1996; Duncan & Lissauer 1998; Debes & Sigurdsson 2002). In principle, each detection of a planet around a giant represents a snapshot of the dynamical evolution of orbits around a particular, evolving star. Given a sufficient number of planet detections, it should be possible to constrain the principal evolutionary scenarios and obtain a consistent picture of dynamical changes in planetary systems in response to the evolution of their parent stars. An excellent example of the analysis of planetary orbits that would be applicable in this context has been presented by Ford et al. (2005).

HD 17092b is the tenth published discovery of a planet around a giant star. It is one of the most distant and metal-rich giants known to host a planetary system. The basic characteristics of the 10 stars and their planets are compared in Table 3. Clearly, the available data are not yet sufficient to fully characterize the emerging population of planets around post-MS stars. One notable exception is a visible paucity of short-period planets, which is not surprising given the dynamical effects of mass loss from and radial expansion of their parent stars (e.g., Duncan & Lissauer 1998). Another possible trend, which may or may not be confirmed later, is that one-half of the planets listed in Table 3 orbit stars with metallicities lower than that of the Sun. This seemingly contradicts the correlation between frequency of occurrence and stellar metallicity found for planets around MS stars by Fischer & Valenti (2005). Further discoveries of planets around giant stars will undoubtedly aid in developing sufficient statistics to meaningfully

TABLE 3  
PLANETS AROUND EVOLVED STARS IN ORDER OF DISCOVERY DATE

Planet	$M_*$ ( $M_\odot$ )	$R_*$ ( $R_\odot$ )	$M_{\text{pl}}$ ( $M_J$ )	$a$ (AU)	$P$ (days)	$e$	[Fe/H]	References
$\iota$ Dra b.....	1.05	12.9	8.9	1.3	536	0.7	+0.05	1
HD 47536 b.....	2.0	21.3	5.0	2.0	712	0.20	-0.61	2
$\gamma$ Cep b.....	1.6	4.7	1.7	2.3	920	0.12	+0.18	3
HD 104985 b.....	1.6	11	6.3	0.78	189	0.03	-0.35	4
HD 11977 b.....	1.9	10.2	6.5	1.9	1420	0.40	-0.14	5
HD 13189 b.....	3.5	...	14	1.8	471	0.27	-0.59	6
$\beta$ Gem b.....	1.7	8.4	2.3	2.4	590	0.02	+0.19	7
$\epsilon$ Tau b.....	2.7	13.7	7.6	1.93	595	0.15	+0.17	8
4 UMa b.....	1.23	18.1	7.1	0.87	269	0.43	-0.25	9
17092 b.....	2.3	10.9	4.6	1.3	360	0.17	+0.22	10

REFERENCES.—(1) Frink et al. 2002; (2) Setiawan et al. 2003; (3) Hatzes et al. 2003; (4) Sato et al. 2003; (5) Setiawan et al. 2005; (6) Hatzes et al. 2005; (7) Hatzes et al. 2006; (8) Sato et al. 2007; (9) Döllinger et al. 2007; (10) this survey.

address these and other important questions of planet formation around intermediate-mass stars and the long-term evolution and survival of planetary systems.

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