A Substellar Companion in a 1.3 yr Nearly-circular Orbit of HD 16760[1,2]

Bun'ei Sato[3], Debra A. Fischer[4], Shigeru Ida[5], Hiroki Harakawa[5], Masashi Omiya[6], John A. Johnson[7], Geoffrey W. Marcy[8], Eri Toyota[9], Yasunori Hori[5], Howard Isaacson[4], Andrew W. Howard[8], and Kathryn M.G. Peek[8]

sato.b.aa@m.titech.ac.jp

Received ————————; accepted ————————

[1]Based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

[2]Based on observations obtained at the W. M. Keck Observatory, which is operated by the University of California and the California Institute of Technology. Keck time has been granted by NOAO and NASA.

[3]Global Edge Institute, Tokyo Institute of Technology, 2-12-1-S6-6 Ookayama, Meguro-ku, Tokyo 152-8550

[4]Department of Physics & Astronomy, San Francisco State University, San Francisco, CA 94132

[5]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551

[6]Department of Physics, Tokai University, 1117 Kitakaname, Hiratsuka, Kanagawa 259-1292

[7]Institute for Astronomy, University of Hawaii, Honolulu, HI 96822

[8]Department of Astronomy, University of California, Berkeley, CA

[9]Kobe Science Museum, 7-7-6 Minatoshima-Nakamachi, Chuo-ku, Kobe, Hyogo 650-0046

Submitted to ApJ

ABSTRACT

We report the detection of a substellar companion orbiting the G5 dwarf HD 16760 from the N2K sample. Precise Doppler measurements of the star from Subaru and Keck revealed a Keplerian velocity variation with a period of 466.47±0.32 d, a semiamplitude of 407.71±0.84 m s^{-1}, and an eccentricity of 0.084±0.002. Adopting a stellar mass of 0.78±0.05 $M_\odot$, we obtain a minimum mass for the companion of 13.13±0.56 $M_{\rm JUP}$, which is close to the planet/brown-dwarf transition, and the semimajor axis of 1.084±0.023 AU. The nearly circular orbit despite the large mass and intermediate orbital period makes this companion unique among known substellar companions.

Subject headings: planetary systems – stars: individual (HD 16760)

1. Introduction

During the past decade, precise Doppler surveys have observed 3000 of the closest and brightest main sequence stars and have detected more than 250 extrasolar planets so far (e.g. Butler et al. 2006; Udry & Santos 2007). The planets show a surprising diversity in their masses, orbital periods, and eccentricities, and the statistical distribution and correlation of these parameters now begin to serve as the test cases for theories of planet formation and evolution (e.g. Ida & Lin 2004a, 2004b, 2005).

Stellar metallicity is one of the key parameters that controls planet formation. It is well known that frequency of giant planets becomes higher as stellar metallicity increases (e.g. Santos et al. 2003; Fischer & Valenti 2005 and references therein). Such a trend favors a core accretion model as the main mechanism of giant planet formation, because high metallicity likely increases the surface density at the midplane of the protoplaentary disk, making it easier to build metal cores massive enough to accrete gas envelope (e.g. Ida & Lin 2004b; Alibert et al. 2004). It has also been noted that there is a possible flat tail in the low-metallicity regime of the frequency distribution (Santos et al. 2004; Sozzetti et al. 2009 in press). This might suggest the existence of a distinct formation mechanism, disk instability, which is not dependent on metallicity (Boss 2002). Correlations between metallicity and orbital parameters are inconclusive. No significant trends have been found in period-metallicity and eccentricity-metallicity distribution, although hints of some weak correlations have been pointed out (e.g. Santos et al. 2003; Fischer & Valenti 2005).

It has also been pointed out that in addition to the presence of gas giant planets, the mass of the detected planet or the total mass of all planets in a system are correlated with high metallicity (e.g., Santos et al. 2003; Fischer & Valenti 2005), as predicted by core accretion. Massive companions with $\gtrsim 10$ Jupiter-mass (M_{JUP}) could be formed by core-accretion depending on the assumed truncation condition for gas accretion (Ida & Lin

2004b; Alibert et al. 2004; Mordasini et al. 2007). Or they could be formed by gravitational disk instability as has been suggested for the formation of brown-dwarf companions. In fact, an upper limit of planet mass has not been well established theoretically or observationally. In core accretion, the limit is regulated by a balance between gap opening (e.g., Ida & Lin 2004a; Crida et al. 2006), the inflow rate due to viscous diffusion and dissipation timescales of protoplanetary disks (e.g. D'Angelo et al. 2003; Dobbs-Dixon et al. 2007; Tanigawa & Ikoma 2007). Planet mass might also depend on subsequent evolution of planets by mechanisms such as giant impacts (Baraffe et al. 2008). In disk instability, planet mass depends primarily on the mass ratio between the disk and central star. Observational properties of planets help to constrain the planet formation models. Currently, no significant difference in stellar metallicity has been found for planets above and below $\sim 10 M_{\rm JUP}$ (e.g., Santos et al. 2003; Fischer & Valenti 2005). Indeed, very high mass planets (i.e., greater than $10 M_{\rm JUP}$) are rare; a larger sample would improve statistics for extracting information regarding the upper limit of planet mass and correlations between planet mass and metallicity.

The N2K consortium began precise Doppler surveys at Keck, Magellan, and Subaru in 2004, targeting a new set of 2000 metal-rich solar-type stars (Fischer et al. 2005). The main purpose of the survey was to search for short-period planets with a high-cadence observational strategy in order to find prospective transiting planets. The sample was biased toward high-metallicity stars in order to increase the detection rate of the planets. From the collective N2K surveys, we have discovered 7 short-period ($P \leq 5$ d) planets so far including: HD 88133 (Fischer et al. 2005), the transiting planet HD 149026 (Sato et al. 2005), HD 149143 and HD 109749 (Fischer et al. 2006), HD 86081, HD 224693, and HD 33283 (Johnson et al. 2006).

The metallicity-biased sample is expected to contain many long-period planets as

well as short-period ones since the fraction of short-period planets is at most 20% among detected extrasolar planets. Therefore, we have continued to observe stars with significant radial velocity variations and we have also detected 13 intermediate-period (18–1405 d) planets: HD 5319 and HD 75898 (Robinson et al. 2007), HD 11506, HD 125612, HD 170469, HD 231701 and the transiting planet HD 17156 (Fischer et al. 2007), the double planet system HIP 14810 (Wright et al. 2007), HD 205732 and HD 154672 (Lopez-Morales 2008), HD 179079 and HD 73534 (Valenti et al 2009 in press). These planets help to investigate correlations between properties of planets and stellar metallicity in more detail, especially in the high-metallicity regime.

Here, we report the discovery of a substellar companion to the G5 dwarf star HD 16760 in a 1.3 yr nearly-circular orbit from the N2K sample. The companion has a minimum mass of 13.13 $M_{\rm JUP}$, which is just above the deuterium-burning threshold that is often used to distinguish brown dwarfs from planets.

2. Stellar Parameters

HD 16760 (HIP 12638) is listed in the Hipparcos catalogue (ESA 1997) as a G5V star with a visual magnitude $V = 8.7$ and a color index $B - V = 0.715$. The Hipparcos parallax of $\pi = 19.93 \pm 2.81$ mas corresponds to a distance of 50.2 pc and yields the absolute visual magnitude of $M_V = 5.41$. The star is probably a visual binary system having a Hipparcos double star catalogue entry. The secondary is separated by 14.6 arcsec which corresponds to a projected separation of about 730 AU. A high-resolution spectroscopic analysis described in Valenti & Fischer (2005) derives an effective temperature $T_{\rm eff} = 5629 \pm 44$ K, a surface gravity $\log g = 4.47 \pm 0.06$, rotational velocity $v \sin i = 0.5 \pm 0.5$ km s^{-1}, and metallicity [Fe/H] $= 0.067 \pm 0.05$ dex for the star. The bolometric luminosity is $L_{star} = 0.72 \pm 0.43 L_{\odot}$ calculated using the M_V and a bolometric correction of -0.108 based on Flower (1996).

The radius of 0.81±0.27 $R_\odot$ for the star is derived from the Stefan-Boltzmann relation using L_{star} and $T_{\rm eff}$.

To estimate a stellar mass, we interpolated the metallicity, effective temperature, and luminosity onto the stellar interior model grids computed by Girardi et al. (2002). We used the three-dimensional interpolation method described by Johnson et al. (2007), and adopt their estimated 7% uncertanty based on a comparison among different stellar model grids. Using the SME–derived stellar parameters, we estimate $0.78 \pm 0.05 M_\odot$ for HD 16760.

As an indicator of chromospheric activity, we measured S_{HK}, the core emission in the Ca II HK lines relative to the continuum, to be 0.176 for the star. The ratio of flux from S_{HK} to the bolometric stellar flux, $\log R'_{HK}$, was derived to be $\log R'_{HK} = -4.93$, which indicates that the star is chromospherically inactive. The expected stellar "jitter", which is intrinsic variability in radial velocity as an additional source of astrophysical noise, was estimated to be 2 m s^{-1} for the star based on the activity and the spectral type from empirical relation by Wright (2005). We applied the jitter to radial velocities from both Subaru and Keck when fitting a Keplerian model in section 3. The stellar parameters are summarized in Table 1.

3. Radial Velocities and Orbital Solutions

Ten radial velocity data of HD 16760 were obtained with the High Dispersion Spectrograph (HDS) on the 8.2 m Subaru Telescope (Noguchi et al. 2002) from December 2004 to February 2008. We used an iodine (I$_2$) absorption cell (Kambe et al. 2002) to provide a fiducial wavelength reference for precise radial velocity measurements. We adopted the setup of StdI2b for all the data, which simultaneously covers a wavelength region of 3500–6100 Å by a mosaic of two CCDs. The slit width was set to 0″.8 for the

first 4 data (2004–2005) and $0''.6$ for the last 6 ones (2006–2008), giving a reciprocal resolution ($\lambda/\Delta\lambda$) of 45000 and 60000, respectively. Typical signal-to-noise ratio (S/N) was 140–200 pix^{-1} with exposure time of 110–300 s depending on the observing conditions. Radial velocity analysis for an I$_2$-superposed stellar spectrum was carried out with a code developed by Sato et al. (2002), which is based on a technique by Butler et al. (1996) and Valenti et al. (1995), giving a Doppler precision of about 4–5 m s^{-1}.

After the first 3 observing runs at Subaru, we identified significant radial velocity variations of the star and then began follow-up observations with the 10-m Keck telescope. Seventeen Keck radial velocity data were obtained with the HIRES spectrograph (Vogt et al. 1994) between Jan 2006 and Jan 2009. We used the B5 decker ($0''.86$ width with a resolution of about $R = 65000$). Exposure times ranged from 150 to 240 seconds depending on the observing conditions, resulting a consistent S/N of about 150. An I$_2$ cell was inserted in the light path to provide the wavelength solution and the instrumental PSF (Marcy et al. 1992; Butler et al. 1996) in our model of the observed spectrum. The typical Doppler precision for the Keck observations is 1.5 m s^{-1}.

The Doppler measurements are listed in Table 2 along with the time of observation, the estimated uncertainties and the origin of the observation (Subaru or Keck). The radial velocities were modeled with a Keplerian orbit using a Levenberg-Marquardt fitting algorithm to obtain a minimum chi-squared solution by varying the free parameters (orbital period, time of periastron passage, eccentricity, velocity amplitude and omega - the orientation of the orbit reference to the line of nodes). The combined radial velocities from Subaru and Keck are plotted in Figure 1 and the best Keplerian fit is overplotted as a solid line. The expected stellar jitter of 2 m s^{-1} was added in quadrature to the velocity uncertainties when fitting the Keplerian orbit and are included in the velocities plotted in Figure 1.

The best fit orbital parameters are listed in Table 3. The uncertainty for each orbital parameter was determined using a bootstrap Monte Carlo approach, subtracting the theoretical fit, scrambling the residuals, adding the theoretical fit back to the residuals and then refitting. The radial velocities are best fit by a Keplerian model with a period $P = 466.47 \pm 0.33$ d, a velocity semiamplitude $K_1 = 407.71 \pm 0.84$ m s^{-1}, and an eccentricity $e = 0.084 \pm 0.002$. An offset of 37 m s^{-1} was applied to the Subaru data in order to minimize reduce chi-squared ($\sqrt{\chi_\nu^2}$) when fitting a Keplerian model to the combined Subaru and Keck velocities. The rms scatter of the residuals to the Keplerian fit is 4.3 m s^{-1}, and the reduce chi-squared is $\sqrt{\chi_\nu^2} = 1.3$. We found no significant additional periodicity in the residuals. Adopting a stellar mass of 0.79 ± 0.05 $M_\odot$, we obtained for the companion a minimum mass $M_p \sin i = 13.13 \pm 0.56$ M_{JUP}, which is close to the planet/brown-dwarf transition, and a semimajor axis $a = 1.084 \pm 0.023$ AU.

If we assume the orbit is randomly oriented, there is a 1.4% chance that the true mass exceeds 80 M_{JUP} ($i < 9.5°$), the boundary between the brown dwarf and stellar mass regime. In this case, the projected semi-major axis is less than 2.1 mas based on the $a_1 \sin i$ and the distance to the star, which is below the measurement error of Hipparcos. We measured a small projected rotational velocity for HD 16760 ($v \sin i = 0.5$ km s^{-1}). This may suggest that a near pole-on viewing angle and thus high mass of the companion is possible if the orbital plane is co-planar to the stellar equator. High-precision spaceborn astrometric observations such as using Hubble Space Telescope, which can achieve ~ 0.3 mas precision (e.g., Bean et al. 2007), are highly encouraged to set a stringent constraint on the mass of the companion.

4. Discussion and Summary

We have reported the discovery of a substellar companion around the G5 dwarf star HD 16760 in a 1.3 yr-orbit from precise Doppler measurements at Subaru and Keck. Although the N2K survey originally targeted short-period planets with a few successive observations, based on the Fischer and Valenti metallicity correlation, we expect that 15% of the target stars harbor gas giant planets. The metallicity-biased sample is expected to contain many long-period planets as well as additional short-period ones.

HD 16760 b has a minimum mass of about 13 $M_{\rm JUP}$, which is close to the border between planet and brown dwarf regimes. By definition, this is a brown dwarf because the mass is above limit for deuterium buring ($13 M_{\rm JUP}$) and in this context it is considered to be part of a low mass tail of the brown-dwarf distribution. However, such a companion is often called a "super-planet" because it could be a high mass tail of the planet distribution too. Core-accretion models of planet formation can predict super-massive planets larger than 10 $M_{\rm JUP}$ or even up to 20–25 $M_{\rm JUP}$ under metal-rich environment, depending on the assumed truncation condition for gas accretion (Ida & Lin 2004b; Alibert et al. 2004; Mordasini et al. 2007). In fact, the upper limit of planet mass has not been well established theoretically, and it should be set based on the observational properties of planets.

Currently, 7 companions with minimum mass of 13–25 $M_{\rm JUP}$ have been detected within semimajor axis of 5 AU around solar-type stars (FGK dwarfs with $0.7 \leq M/M_\odot < 1.6$) by precise Doppler measurements including a transiting one CoRoT-Exo-3 b for which accurate mass of 21.7 $M_{\rm JUP}$ was obtained (Deleuil et al. 2008). The number of such companions is still small and their statistical properties have not yet been established. In Figure 2, the planet eccentricity is plotted against planet mass. As pointed out by Marcy et al. (2005), the more massive planets ($\gtrsim 5 M_{\rm JUP}$) have systematically higher eccentricities than lower-mass planets. Most companions with $> 8 M_{\rm JUP}$ (other than HD 16760 b and HD

168443 c[1]) have eccentricities larger than about 0.3 except for planets in short-period orbits where tidal circularization could be effective.

Since massive companions have the largest inertial resistance to perturbations that drive them out of their initial orbits, they should retain their initial orbits. Therefore, massive planets with high eccentricity are difficult to explain within the framework of standard core accretion model. This suggests a distinct evolutionary scenario that could result in eccentric orbits for massive companions, such as disk instability (e.g. Boss 1998), giant impacts between massive planets following core accretion (Baraffe et al. 2008), or orbital evolution by Kozai mechanism for binary stars (e.g. Wu & Murray 2003). The fact that HD 16760 is probably in a binary system but the companion has a small eccentricity is interesting from this view point of orbital evolution with respect to the Kozai mechanism.

The metallicity of the host stars may be one of the keys to distinguishing between planet formation models; disk instability is not dependent on metallicity (Boss 2002), while accretion should be more efficient in high metallicity disks. We do not observe a correlation between metallicity and eccentricity for the most massive companions at this stage. However, there are still only a small number of these objects.

In summary, HD 16760 b is unique among the known substellar companions because it resides in a nearly-circular orbit with an intermediate orbital period and a mass that is greater than 13 times the mass of Jupiter. Detection of additional objects in this mass regime could provide deeper insight for theoretical models.

---

[1]HD 168443 has two planets; one is 8 $M_{\rm JUP}$ (b) and the other is 18 $M_{\rm JUP}$ (c)

REFERENCES

Alibert, Y., Mordasini, C., Benz, W., Winisdoerffer, C. 2005, A&A, 434, 343

Baraffe, I., Chabrier, G., & Barman, T. 2008, A&A, 482, 315

Bean, J. L., McArthur, B. E., Benedict, G.F., Harrison, T.E., Bizyaev, D., Nelan, E., & Smith, V.V., 2007, AJ, 134, 749

Boss, A.P. 1998, ApJ, 503, 923

Boss, A.P. 2002, ApJ, 567, L149

Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500

Butler, R.P., et al., 2006, ApJ, 646, 505

Crida, A., Morbidelli, A., & Masset, F. 2006, Icarus, 181, 587

D'Angelo, G., Kley, W., & Henning, T., 2003, ApJ, 586, 540

Deleuil, M., et al. 2008, A&A, 491, 889

Dobbs-Dixon, I., Li, S.L., & Lin, D. N. C., 2007, ApJ, 660, 791

ESA 1997. The Hipparcos and Tycho Catalogs. ESA-SP 1200

Fischer, D.A. & Valenti, J. 2005, ApJ, 622, 1102

Fischer, D.A., et al., 2007 ApJ, 669, 1336

Fischer, D.A., et al., 2006 ApJ, 637, 1094

Fischer, D.A., et al., 2005 ApJ, 620, 481

Flower, P. J. 1996, ApJ, 469, 355

Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M.A.T., Marigo, P., Salasich, B., & Weiss, A. 2002, A&A, 391, 195

Ida, S. & Lin, D.N.C. 2004a, ApJ, 604, 388

Ida, S. & Lin, D.N.C. 2004b, ApJ, 616, 567

Ida, S. & Lin, D.N.C. 2005, ApJ, 626, 1045

Johnson, J.A., et al., 2006 ApJ, 647, 600

Johnson, J.A., et al., 2007 ApJ, 665, 785

Kambe, E. et al. 2002, PASJ, 54, 873

Lopez-Morales, M., et al., 2008 AJ, 136, 1901

Marcy, G.W., & Butler, R.P. 2002, PASP, 104, 270

Marcy, G.W. et al., 2005 Prog. Theor. Phys. Suppl. 158, 24

Mordasini, C., Alibert, Y., Benz, W., & Naef, D. 2007, in "Extreme Solar Systems", ASP Conf. Ser. Vol. 398, 235

Noguchi, K. et al. . 2002, PASJ, 54, 855

Santos, N.C., Israelian, G., Mayor, M., Rebolo, R., & Udry, S. 2003, A&AS, 398, 363

Santos, N.C., Israelian, G., & Mayor, M., 2004, A&AS, 415, 1153

Sato, B., et al., 2005 ApJ, 633, 465

Sato, B., Kambe, E., Takeda, Y., Izumiura, H., & Ando, H. 2002, PASJ, 54, 873

Takeda, G., Ford, E.B., Sills, A., Rasio, F., Fischer, D.A., & Valenti, J.A. 2007, ApJS, 168, 297

Tanigawa, T., & Ikoma, M. et al. 2007, 667, 557

Valenti, J. A., Butler, R. P., & Marcy, G. W. 1995, PASP, 107, 966

Valenti, J. A., & Fischer, D.A. 2005, ApJS, 159, 141

Vogt, S.S., et al. 1994, Proc. SPIE, 2198, 362

Wright, J. T., 2005 PASP, 117, 657

Wright, J. T., et al., 2007 ApJ, 657, 533

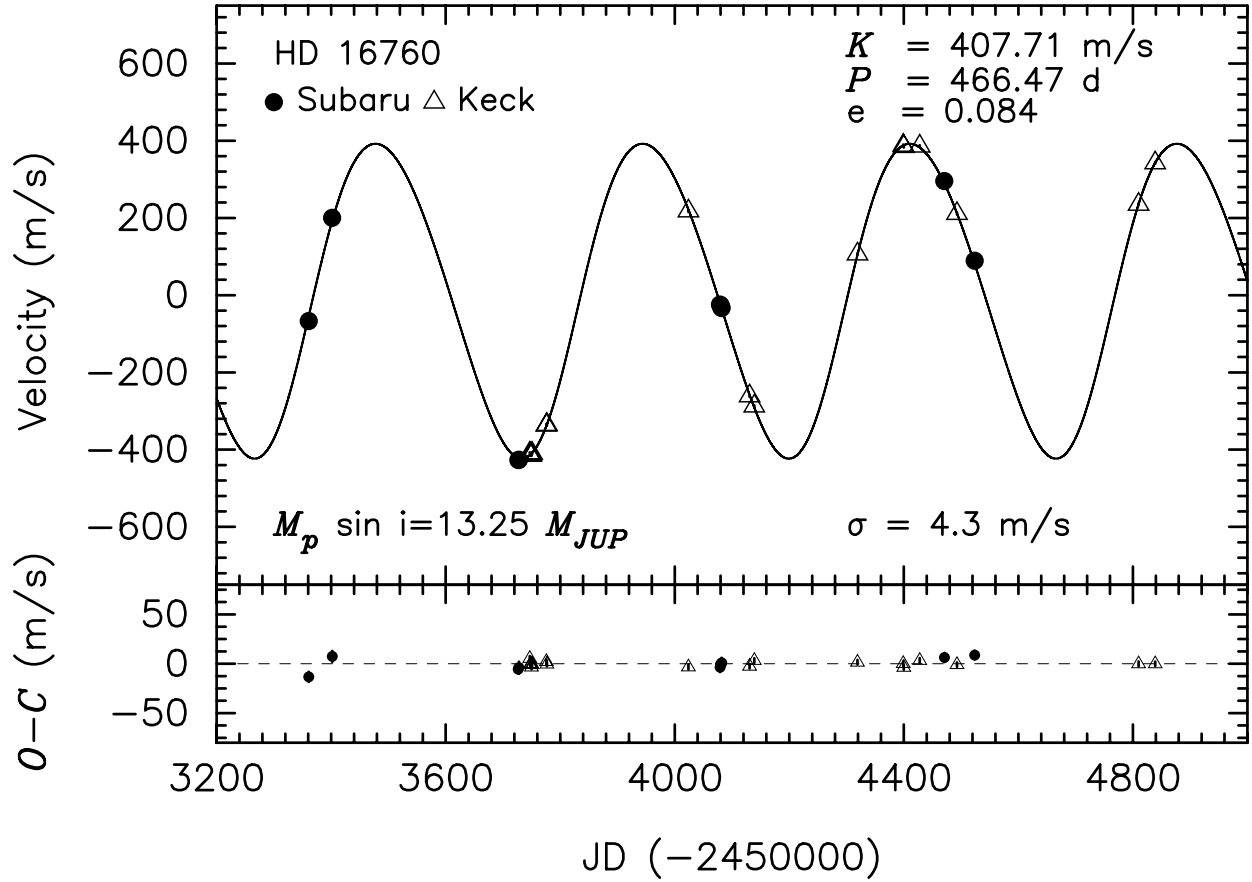Wu, Y. & Murray, N., 2003, ApJ, 589, 605

Fig. 1.— Radial velocities for HD 16760 from Subaru (filled circles) and Keck (open triangles).
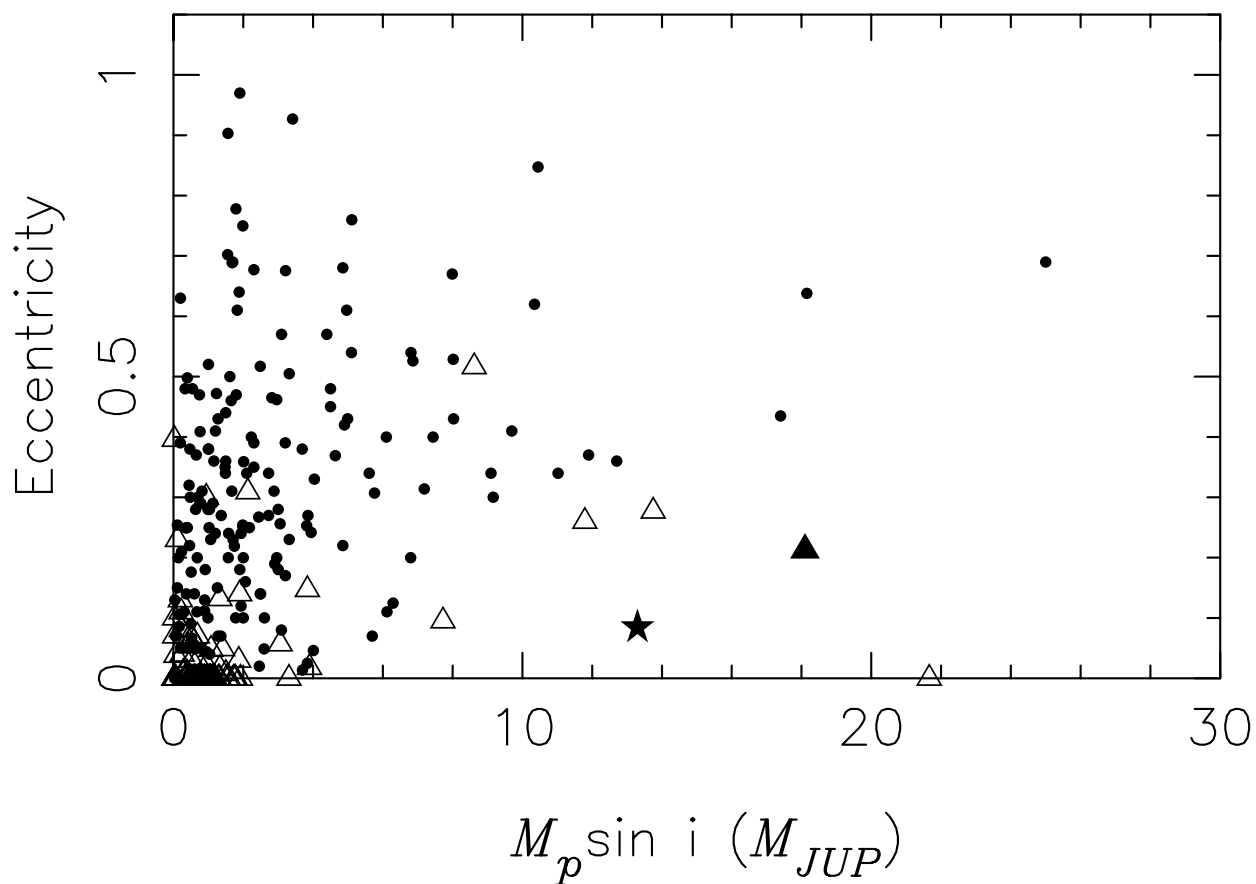
Fig. 2.— Eccentricity plotted against minimum mass of the planet. HD 16760 b is plotted with *star*. HD 168443 c is plotted with filled triangle, in which system there is another planet with 8 M_J (HD 168443 b). CoRoT-Exo-3 b, a transiting brown dwarf/super-planet, has a mass of 21.7 M_J without $\sin i$ ambiguity in a 4.26-d orbit. Planets with $a < 0.1$AU (*open triangle*) may be affected by tidal effect. Only planets around FGK dwarfs are plotted in the figure (data from http://exoplanet.eu).

Table 1. Stellar Parameters for HD 16760

Parameter	Value
V	8.7
M_V	5.41
$B - V$	0.715
$B.C.$	-0.108
Spectral type	G5V
Parallax (mas)	19.93 (2.81)
$T_{\rm eff}$ (K)	5629 (44)
$\log g$	4.47 (0.06)
[Fe/H]	$+0.067$ (0.05)
$v \sin i$ (km s^{-1})	0.5 (0.5)
M_{STAR} ($M_\odot$)	0.78 (0.05)
R_{STAR} ($R_\odot$)	0.81 (0.27)
L_{STAR} ($L_\odot$)	0.72 (0.43)
S_{HK}	0.176
$\log R'_{HK}$	-4.93

Table 2: Radial Velocities for HD 16760

JD −2450000	Radial Velocity (m s^{-1})	Uncertainties (m s^{-1})	Observatory
3360.89840	−67.01	4.66	Subaru
3401.87152	200.38	5.28	Subaru
3726.87567	−427.26	4.15	Subaru
3727.85200	−426.31	5.70	Subaru
3746.81122	−409.23	1.28	Keck
3747.87456	−414.10	1.24	Keck
3748.78525	−411.79	1.20	Keck
3749.78054	−413.81	1.16	Keck
3750.79189	−409.55	1.15	Keck
3775.77328	−336.64	0.95	Keck
3776.81038	−335.11	1.25	Keck
4023.95588	217.93	1.50	Keck
4078.93737	−24.05	4.52	Subaru
4079.92984	−26.00	4.99	Subaru
4080.99173	−30.70	4.60	Subaru
4081.88938	−33.80	4.83	Subaru
4130.74043	−261.06	1.10	Keck
4138.79826	−287.38	1.11	Keck
4319.10806	106.52	1.14	Keck
4398.95389	387.91	1.13	Keck
4399.88492	384.74	1.36	Keck
4427.84750	385.80	1.43	Keck
4470.89963	295.34	4.17	Subaru
4492.75215	211.30	1.10	Keck
4523.74114	89.43	4.05	Subaru
4809.84453	235.27	1.52	Keck
4838.85261	342.52	1.02	Keck

Table 3.   Orbital Solution for HD 16760b

Parameter	Value
P (days)	466.47 (0.32)
$T_{\rm p}$ (JD)	2453337.0 (2.1)
Eccentricity	0.084 (0.002)
ω (deg)	242.9 (1.7)
K_1 (m s^{-1})	407.71 (0.84)
a (AU)	1.084 (0.023)
$a_1 \sin i$ (10^{-3}AU)	17.420 (0.042)
f_1(m) ($10^{-6}M_\odot$)	3.241 (0.021)
$M_p \sin i$ ($M_{\rm JUP}$)	13.13 (0.56)
N$_{\rm obs}$ (Subaru)	10
N$_{\rm obs}$ (Keck)	17
RMS (m s^{-1})	4.3
Reduced $\sqrt{\chi_\nu^2}$	1.3