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DETECTION OF A NEPTUNE-MASS PLANET IN THE ρ^1 CANCRI SYSTEM USING THE HOBBY-EBERLY TELESCOPE

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ABSTRACT

We report the detection of the lowest mass extrasolar planet yet found around a Sun-like star—a planet with an $M \sin i$ of only $14.21 \pm 2.91\ M_\oplus$ in an extremely short period orbit ($P = 2.808$ days) around ρ^1 Cancri, a planetary system that already has three known planets. Velocities taken from late 2003–2004 at McDonald Observatory with the Hobby-Eberly Telescope revealed this inner planet at 0.04 AU. We estimate an inclination of the outer planet ρ^1 Cancri d, based on *Hubble Space Telescope* Fine Guidance Sensor measurements that suggest an inner planet of only $17.7 \pm 5.57\ M_\oplus$, if coplanarity is assumed for the system.

Subject headings: astrometry — planetary systems — stars: individual (ρ^1 Cancri)

Online material: machine-readable table

1. INTRODUCTION

Of the numerous planets found so far around main-sequence stars, there are 13 multiple-planet systems. The fourth extrasolar planet discovered was the 14.65 day period planet around ρ^1 Cancri ($= \rho$ Cancri A $=$ 55 Cancri 1 $=$ HD 75732 $=$ HIP 43587 $=$ HR 3522; Butler et al. 1997). More recently, the orbits of an additional outer planet and a possible intermediate planet have been reported (Marcy et al. 2002). In this Letter, we announce the discovery of a fourth inner planet in the ρ^1 Cancri system with a radial velocity semiamplitude (K) of 6.7 m s^{-1}, an orbital period of 2.808 days, $M \sin i$ of $0.04 M_J$, and a probable actual mass of $0.056 M_J$ ($17.7\ M_\oplus$).

ρ^1 Cancri appears to be a super–metal-rich (G8 V, $V = 5.95$, [Fe/H] $= +0.27$) but otherwise normal main-sequence star with a $V = 13$ visual binary companion. There is no detectable circumstellar disk around ρ^1 Cancri (Jayawardhana et al. 2002; Schneider et al. 2001). The metallicity is significantly higher than the mean of nearby field stars but is in accord with the trend of close-in giant planets being found preferentially around metal-rich solar-type and cooler stars (Taylor 1996; Gonzalez & Vanture 1998; Feltzing & Gonzalez 2001; Cayrel de Strobel et al. 2001; Laws et al. 2003; Heiter & Luck 2003). Mass estimates for ρ^1 Cancri range from 0.88 to 1.08 $M_\odot$ (Laws et al. 2003; Fuhrmann et al. 1998; Ford et al. 1999). We adopt a mass of $0.95 \pm 0.08\ M_\odot$ (C. Allende-Prieto 2004, private communication).

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2. OBSERVATIONS AND RESULTS

2.1. *Hubble Space Telescope Astrometry*

This Letter made use of reanalyzed public domain data (B. E. McArthur et al. 2004, in preparation) obtained from the *Hubble Space Telescope* (*HST*; McGrath et al. 2003) to provide an estimate of the inclination of the long-period planet ρ^1 Cancri d. For the parameters critical in determining the mass of ρ^1 Cancri d, we find a parallax $\pi_{abs} = 79.78 \pm 0.3$ mas, a perturbation size $\alpha = 1.94 \pm 0.4$ mas, and an inclination $i = 53° \pm 6\overset{\circ}{.}8$. The inclination was derived from a small arc of orbit coverage in the limited *HST* data set. In any case, an inclination of less than 20° cannot be considered because of the very large perturbation that could not have been missed, even by the small existing sample of *HST* astrometric data.

2.2. *Radial Velocity*

We used the Hobby-Eberly Telescope (HET) to make numerous high-precision radial velocity observations of ρ^1 Cancri over a short time period in preparation for anticipated additional *HST* astrometry, knowing that these observations would also be able to uncover any additional planetary companions with radial velocities greater than 3 m s^{-1} and orbital periods of a year or less. The HET High-Resolution Spectrograph, used in conjunction with an I_2 gas absorption cell, can give routine high-precision radial velocities of 3 m s^{-1} for high signal-to-noise ratio observations (Cochran et al. 2004). By taking advantage of the queue-scheduled operation of the HET, we recorded well over 100 radial velocity measurements in a span of about 190 days, shown in Table 1. This "snapshot" of the ρ^1 Cancri system provides the best definition of the orbital parameters of the two known short-period inner planets because it is relatively free of time-varying changes, not only in the planetary system but also in the facilities used to observe the system.

The long-period planet (ρ^1 Cancri d) clearly could not be modeled by the HET data alone, but because of its velocity amplitude it played a very critical part in the initial modeling of the triple-Keplerian orbit. Three sets of radial velocity (RV) data from Lick (Marcy et al. 2002), ELODIE (Naef et al. 2004), and HET were fitted with a triple-Keplerian orbit using *Gaussfit* (Jefferys et al. 1987), employing the technique of combining

TABLE 1
MEASURED VELOCITIES FOR ρ^1 CANCRI

Julian Date	Radial Velocity (m s^{-1})	Uncertainty (m s^{-1})
2,452,927.984100	48.3959	4.42
2,452,927.986693	45.2119	4.61
2,452,928.973951	32.9745	4.33
2,452,928.976555	33.8595	4.00
2,452,929.976107	10.1059	4.01

NOTES.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

RVs from different sources (Hatzes et al. 2000) in order to produce the orbit of the outer planet shown in Figure 1. The orbit derived for this long-period planet was then used as a constant in further modeling.

The planet ρ^1 Cancri c was discussed (Marcy et al. 2002) as a signal that could possibly be caused by the rotation modulation of inhomogeneous surface features. The stellar rotation period of 36–42 days was uncovered from periodicities in the Ca II emission (Henry et al. 2000; Noyes et al. 1984). However, the planetary hypothesis is more likely because ρ^1 Cancri is a very inactive star in which RV effects induced by stellar activity generally do not exceed 3.0 m s^{-1}. The amplitude of the signal for this intermediate planet was over 12.0 m s^{-1}. The phased HET data showing ρ^1 Cancri c are shown in Figure 2. Figure 3 shows ρ^1 Cancri b, the original planet found around ρ^1 Cancri.

Analysis of the residuals of the HET data, after removal of the best overall fit to the orbits of the three known planets of all of the radial velocity and astrometric data, revealed a velocity perturbation with a period of 2.808 days. Simultaneous modeling of ρ^1 Cancri b, ρ^1 Cancri c, and ρ^1 Cancri e, with ρ^1 Cancri d as a constant, showed an object in a low-eccentricity orbit with a period of 2.808 $\pm$ 0.002 days. The radial velocity semiamplitude of this orbit is only 6.67 $\pm$ 0.81 m s^{-1}, which is above the expected internal radial velocity "jitter" variability for this star. The 2.808 day radial velocity signal is coherent over the entire time span of the HET data, which would not be expected for stochastically excited stellar surface sources. The HET residuals, phased to the 2.808 day period with the orbital solution overplotted, are show in Figure 4. In retrospect, the clear signal

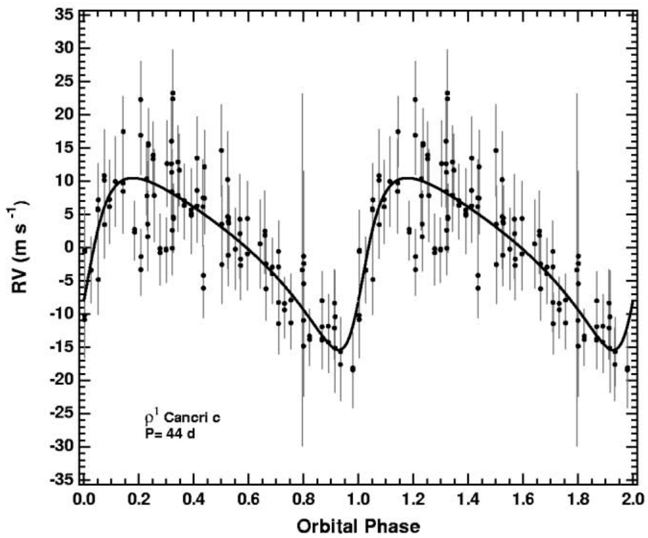

FIG. 2.—RV orbit of the 44 day planet ρ^1 Cancri d is shown with the phased HET data. Two cycles are plotted. The signatures of ρ^1 Cancri b, ρ^1 Cancri d, and ρ^1 Cancri e have been subtracted from the observations.

of this 2.808 day orbital period planet can be seen (along with the signal of the 44 day periodicity [ρ^1 Cancri c]) in Figure 9 of Marcy et al. (2002), which shows the periodogram of the residuals of the Lick data, after ρ^1 Cancri b and d have been removed. This is independent confirmation showing us that this radial velocity periodicity is intrinsic to the ρ^1 Cancri system and not an artifact of the observation or data analysis techniques used on either the HET or Lick data. The 2.808 day periodic signal has a false-alarm probability of 1.7×10^{-9} in the HET data (as seen in Fig. 5) and 1.1×10^{-6} in the Lick data, giving further strong evidence of its reality. We interpret this 2.808 day radial velocity periodicity as the stellar reflex motion due to an extremely low mass planet in orbit around the star. Properties of the combined four-planet orbital solution to all of the radial velocity data are given in Table 2. Mass parameters and limits are shown in Table 3. The HET data in time overplotted with the quad-Keplerian fit are shown in Figure 6. The mass function from the radial velocity solution, combined with our assumed

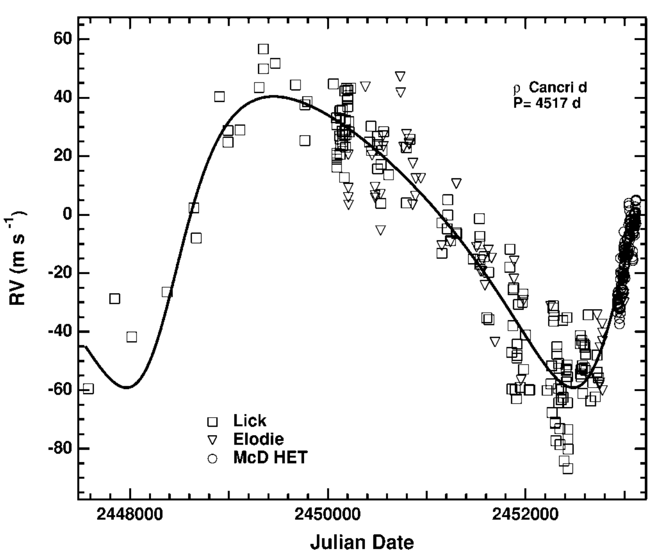

FIG. 1.—RV orbit of the long-period planet ρ^1 Cancri d is shown with the three data sets; ρ^1 Cancri b and ρ^1 Cancri c are subtracted from the observations. The rms of the HET residuals in this fit is 9.2 m s^{-1}.

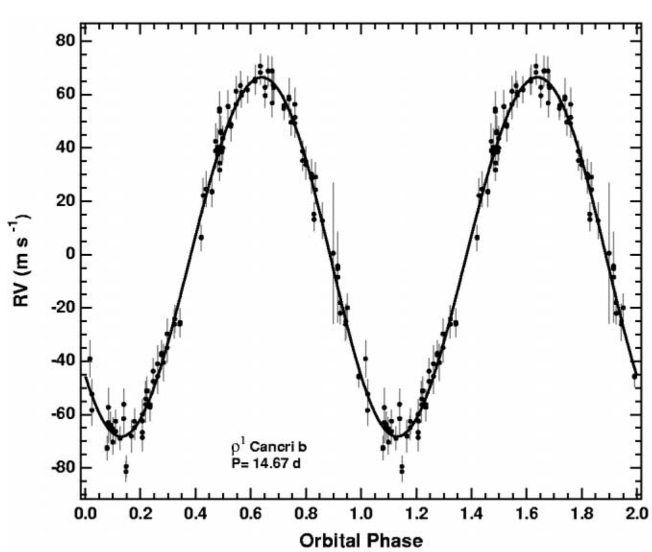

FIG. 3.—RV orbit of the 14.66 day panet ρ^1 Cancri b is shown with the phased HET data; ρ^1 Cancri c, ρ^1 Cancri d, and ρ^1 Cancri e are subtracted from the observations.

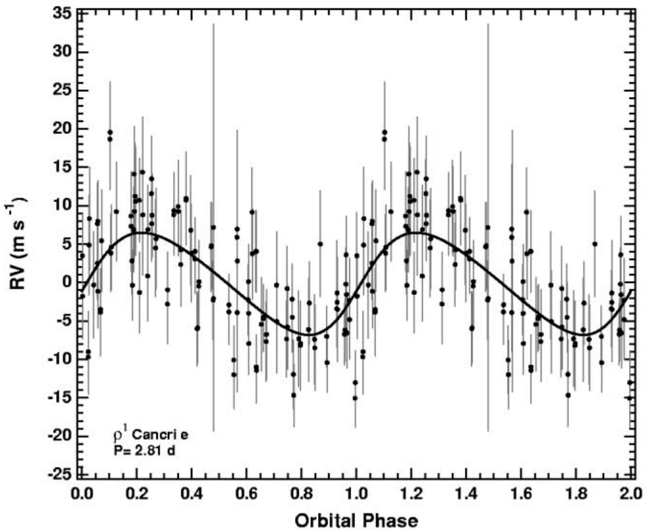

FIG. 4.—RV orbit of the 2.808 day planet ρ^1 Cancri e is shown with the phased HET data. The ρ^1 Cancri b, ρ^1 Cancri c, and ρ^1 Cancri d planets are subtracted from the observations. The rms of the HET residuals in this fit is 5.4 m s^{-1}.

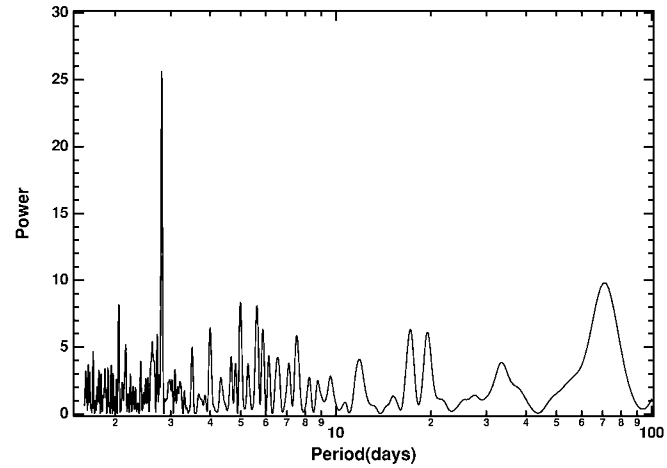

FIG. 5.—Periodogram of the velocity residuals of the HET data, after the orbits of ρ^1 Cancri b, ρ^1 Cancri c, and ρ^1 Cancri d have been subtracted from the original velocities. The peak at 2.808 days has a false-alarm probability of 1.730796E−09.

stellar mass of $0.95 \pm 0.08\ M_{\odot}$, gives an $M \sin i$ for this innermost 2.808 day planet of $(0.045 \pm 0.01)M_J$. If we assume that all of the planets in the ρ^1 Cancri system are coplanar and adopt the 53° inclination of the outermost planet, then we compute a true mass for this innermost planet of about 17.7 $M_{\oplus}$, close to the mass of Neptune. (If an inclination of 20° is assumed, an upper limit of $2.37 M_N$ is derived.) This fourth planet, ρ^1 Cancri b, is the lowest mass extrasolar planet yet found around a solar-type star (we note that the lowest mass extrasolar planets ever found are those around the millisecond pulsar PSR B1247+1221 [Wolszczan & Frail 1992]).

3. DISCUSSION AND CONCLUSION

The inclination of ρ^1 Cancri e, assuming coplanarity of the system, indicates that this object is indeed a Neptune-mass object and not a more massive planet viewed nearly face-on to its orbit. The presence of this very low mass planet at such a small semimajor axis in a system of at least three other gas-giant planets provides a premier laboratory for the modeling of planetary system formation and evolution.

A crucial question is whether ρ^1 Cancri e originally formed at something near the current observed mass or whether it formed as an intermediate or much more massive gas giant that has lost a significant amount of mass during the evolution of the system.

It is reasonable to assume that at least the three inner planets of the ρ^1 Cancri system were formed at roughly the same time and that their dynamical evolution was closely linked. The most massive of these three planets, ρ^1 Cancri b ($P = 14.66$ days), would have been the first to achieve a mass sufficient to open a gap in the disk and begin type II migration (Ward 1997). If this happened before the inner planet ρ^1 Cancri e reached the critical mass for rapid accumulation of a gas envelope, then it could have been carried inward as part of the overall migration of the disk material without ever growing past the rocky core phase (Lin & Papaloizou 1986). Whether this inward tidal migration driven by ρ^1 Cancri b would sweep such a Neptune-mass planet into the stellar photosphere or leave it in its present short-period orbit depends on the details of the end process of planetary tidal evolution. If the planet formed at a mass near its present mass by the core-accretion model of planetary system formation (Pollack et al. 1996), it would be a rocky body that could have a substantial dense atmosphere.

An alternative hypothesis is that ρ^1 Cancri e formed as a much more massive gas-giant planet before it began its inward type II migration to its present orbital radius (Ida & Lin 2004). With the planet then within 0.05 AU of the parent star, it could have suffered from significant heating from tidal interactions with the star (Bodenheimer et al. 2001). This tidal heating could have caused the radius of the planet to inflate, possibly overflowing the Roche radius of the star and resulting in significant planetary mass loss (Gu et al. 2003; Baraffe et al. 2004). It is possible that the mass loss has stripped this planet of almost all of its original H_2-He gas envelope, leaving just the rocky planetary "core." This loss of a gas envelope for very short period planets is supported by the observation of an extended H I, O I, and C II atmosphere around HD 209458b (Vidal-Madjar et al. 2003, 2004), which may be in hydrodynamic

TABLE 2
QUAD-KEPLERIAN ORBITAL ELEMENTS OF ρ^1 CANCRI

Element	ρ^1 Cancri e	ρ^1 Cancri b	ρ^1 Cancri c	ρ^1 Cancri d
Orbital period P (days)	2.808 ± 0.002	14.67 ± 0.01	43.93 ± 0.25	4517.4 ± 77.8
Epoch of periastron T [a]	3295.31 ± 0.32	3021.08 ± 0.01	3028.63 ± 0.25	2837.69 ± 68.87
Eccentricity e	0.174 ± 0.127	0.0197 ± 0.012	0.44 ± 0.08	0.327 ± 0.28
ω (deg)	261.65 ± 41.14	131.49 ± 33.27	244.39 ± 10.65	234.73 ± 6.74
Velocity amplitude K (m s^{-1})	6.665 ± 0.81	67.365 ± 0.82	12.946 ± 0.86	49.786 ± 1.53
V_0 Lick (m s^{-1})	21.166 ± 1.31	…	…	…
V_0 ELODIE (m s^{-1})	2727.448 ± 2.42	…	…	…
V_0 HET (m s^{-1})	10.745 ± 0.59	…	…	…

[a] Add 2,450,000.0 to T.

TABLE 3
ρ^1 CANCRI: MASS LIMITS AND PARAMETERS

Parameter	ρ^1 Cancri e	ρ^1 Cancri b	ρ^1 Cancri c	ρ^1 Cancri d
a (AU)	0.038 ± 0.001	0.115 ± 0.003	0.240 ± 0.008	5.257 ± 0.208
$A \sin i$ (AU)	1.694E−6 ± 0.19E−6	9.080E−5 ± 0.12E−5	4 .695E−5 ± 0.14E−5	0.195E−1 ± 0.007E−1
Mass fraction ($M_\odot$)	8.225E−14 ± 2.33E−14	4.64E−10 ± 0.17E−10	7.151E−12 ± 0.54E−12	4.874E−08 ± 0.38E−8
$M \sin i$ (M_J)[a]	0.045 ± 0.01	0.784 ± 0.09	0.217 ± 0.04	3.912 ± 0.52
$M \sin i$ (M_N)[a]	0.824 ± 0.17	…	…	…
$M \sin i$ ($M_\oplus$)[a]	14.210 ± 2.95	…	…	…
M (M_J)[b,c]	0.056 ± 0.017	0.982 ± 0.19	0.272 ± 0.07	4.9 ± 1.1
M (M_J)[c,d]	0.053 ± 0.020	0.982 ± 0.26	0.244 ± 0.07	4.64 ± 1.3
M (M_N)[c,d]	1.031 ± 0.34	…	…	…
M ($M_\oplus$)[c,d]	17.770 ± 5.57	…	…	…

[a] Derived from radial velocity alone.
[b] Derived from radial velocity and astrometry, using $M \sin i / \sin i$.
[c] Assuming coplanarity of the planetary system.
[d] Derived from radial velocity and astrometry, using $m2^3/(m1 + m2)^2 = a^3/P^2$.

escape from the planet (Lecavelier et al. 2004). However, the discovery of transiting Jupiter-mass planets (OGLE-TR-113 and OGLE-TR-132) with orbital periods of less than 2 days (Bouchy et al. 2004) may cast doubt on this scenario. Both of the OGLE planets are about $1M_J$ and are only slightly greater than $1R_J$. This indicates that planets much more massive than ρ^1 Cancri e can indeed survive at even shorter semimajor axes.

We have shown that an intense campaign of directed observations of a planetary system, aided by previous observations from other telescopes, can uncover Neptune-mass objects. While it will be years before astrometric missions (*SIM* and *GAIA*) will be able to uncover the astrometric perturbation orbits of all these planets, we have been able to use *HST* data to place a preliminary limit on the inclination of the outer planets.

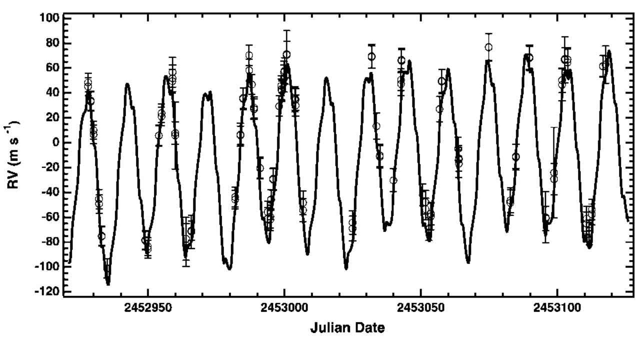

FIG. 6.—Keplerian RV orbit of the four planets (combined) around ρ^1 Cancri shown with the HET data.

The Hobby-Eberly Telescope (HET) is a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig Maximillians Universität München, and Georg August Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. These results are partially based on data obtained with the UCO/Lick Observatory Telescope, the Apache Point Observatory 3.5 m telescope (which is owned and operated by the Astrophysical Research Consortium), and the NASA/ESA *Hubble Space Telecope* (obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc). This Letter is based on work supported by NASA under grants HST GO-09969, NAG5-13206, and NNG04G141G and by the NSF under grant AST-9808980. We are grateful to Ed Nelan for providing the *HST* data, to Melissa McGrath for supporting our further investigation, and to W. Spiesman and an anonymous referee for their careful reading of this manuscript and their thoughtful comments.

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