Kepler-62: A Five-Planet System with Planets of 1.4 and 1.6 Earth Radii in the Habitable Zone
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Small ion trap quantum simulators such as that reported here may soon reach this milestone with technical upgrades in the hardware, including lower vacuum chamber pressures to prevent collisions with the background gas, better stability of the optical intensities, and higher optical power so that fluctuations in the beam inhomogeneities can be suppressed.

References and Notes
18. See supplementary materials on Science Online.
25. Quantum Monte Carlo algorithms can be used to calculate static equilibrium properties of the transverse field Ising model for large numbers of interacting spins, so that ground states and static correlation functions can indeed be calculated for large systems (23). However, the calculation of dynamics and nonequilibrium behavior of quantum spin models is not currently feasible for these Monte Carlo approaches, and in the presence of frustrated long-range interactions, the general behavior of such systems requires exact diagonalization. Other techniques such as the density matrix renormalization group become too difficult with long-range interactions. Because the size of the Hilbert space grows exponentially with the number of spins, sparse-matrix techniques such as the Lanczos method must therefore be used. Current state-of-the-art work on such systems is limited to sizes on the order of 30 to 35 spins (24).

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Supplementary Materials
www.sciencemag.org/cgi/content/full/340/6132/583/DC1
Supplementary Text
Fig. S1
References (26–28)
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Kepler-62: A Five-Planet System with Planets of 1.4 and 1.6 Earth Radii in the Habitable Zone


We present the detection of five planets—Kepler-62b, c, d, e, and f—of size 1.31, 0.54, 1.95, 1.61 and 1.41 Earth radii (R⊕), orbiting a K2V star at periods of 5.7, 12.4, 18.2, 122.4, and 267.3 days, respectively. The outermost planets, Kepler-62e and -62f, are super-Earth–size (1.25 R⊕ < planet radius ≤ 2.0 R⊕) planets in the habitable zone of their host star, respectively receiving 1.2 ± 0.2 times and 0.41 ± 0.05 times the solar flux at Earth’s orbit. Theoretical models of Kepler-62e and -62f for a stellar age of ~7 billion years suggest that both planets could be solid, either with a rocky composition or composed of mostly solid water in their bulk.

Kepler is a NASA Discovery-class mission designed to determine the frequency of Earth-radius planets in and near the habitable zone (HZ) of solar-like stars (J–O). Planets are detected as “transits” that cause the host star to appear periodically fainter when the planets pass in front of it along the observer’s line of sight. Kepler-62 [Kepler Input Catalog (KIC) 9002278, Kepler Object of Interest (KOI) 701] is one of about 170,000 stars observed by the Kepler spacecraft. On the basis of an analysis of long-cadence photometric observations from Kepler taken in quarters 1 through 12 (13 May 2009 through 28 March 2012), we report the detection of five planets orbiting Kepler-62, including two super–Earth-size planets in the HZ as well as a hot Mars-size planet (Fig. 1 and Table 1). Before validation, three of these objects were designated as planetary candi-
We then estimated the frequency of the allowed blends by taking into account all available observational constraints from the follow-up observations discussed in (9). Finally, we compared this frequency with the expected frequency of true planets (planet “prior”) to derive the odds ratio (9). By incorporating these constraints into a Monte Carlo model that considered a wide range of stellar and planetary characteristics, we determined estimates of the probability of each false positive that could explain the observations (9).

Our simulations of each of the candidates indicate that the likelihood of a false-positive explanation is much smaller than the likelihood that the candidates constitute a planetary system. The calculated odds ratios that Kepler-62b through -62f represent planets rather than false positives are 5400, >5000, 15,000, 14,700, and >5000, respectively (9). There is also a 0.2% chance that the planets orbit a widely spaced binary composed of two K2V stars; if so, the planets are larger in radius than the values shown in Table 1 by a factor of \( \sqrt{2} \) (9).

To determine whether a planet is in the HZ, we calculated the flux of stellar radiation that it intercepts. It is convenient to express intercepted flux in units of the average solar flux intercepted by Earth, denoted by \( S_E \). The values of the stellar flux intercepted by Kepler-62b to -62f are \( 70 \pm 9 \, S_E \), \( 25 \pm 3 \, S_E \), \( 15 \pm 2 \, S_E \), \( 1.2 \pm 0.2 \, S_E \), and \( 0.41 \pm 0.05 \, S_E \), respectively. Eccentric planetary orbits increase the annually averaged irradiation from the primary star by a factor of \( 1 + e^2 \) (9).

The HZ is defined here as the annulus around a star where a rocky planet with a \( \text{CO}_2-\text{H}_2\text{O}-\text{N}_2 \) atmosphere and sufficiently large water content (such as on Earth) can host liquid water on its solid surface (20). In this model, the locations of the two edges of the HZ are determined on the basis of the stellar flux intercepted by the planet and the assumed composition of the atmosphere. A conservative estimate of the range of the HZ (labeled “narrow HZ” in Fig. 3) is derived from atmospheric models by assuming that the planets have \( \text{H}_2\text{O} - \text{CO}_2 \)-dominated atmospheres with no cloud feedback (21). The flux range is defined at the inner edge by thermal runaway due to saturation of the atmosphere by water vapor and at the outer edge by the freeze-out of \( \text{CO}_2 \). In this model, the planets are assumed to be geologically active and climatic stability is provided by a mechanism in which atmospheric \( \text{CO}_2 \) concentration varies inversely with planetary surface temperature.

The “empirical” HZ boundaries are defined by the solar flux received at the orbits of Venus and Mars at the epochs when they potentially had liquid water on their surfaces. Venus and Mars are believed to have lost their water at least 1 billion years and 3.8 billion years ago, respectively, when the Sun was less luminous. At these epochs, Venus received a flux of 1.78 \( S_E \) and Mars a flux of 0.32 \( S_E \) (20). The stellar spectral energy distributions of stars cooler than the Sun are expected to slightly increase the absorbed flux (20). Including this factor changes the HZ flux limits to 1.66 and 0.27 \( S_E \) for the empirical HZ, and 0.95 and 0.29 \( S_E \) for the narrow HZ (21). Figure 3 shows that Earth and Kepler-62f are within the flux boundaries of the narrow HZ, whereas Kepler-22b and Kepler-62e are within the empirical flux boundaries.

Although RV observations were not precise enough to measure masses for Kepler-62e and -62f, other exoplanets with a measured radius below 1.6 \( R_\oplus \) have been found to have densities indicative of a rocky composition. In particular, Kepler-10b (22), Kepler-36b (23), and CoRoT-7b (24) have radii of 1.42 \( R_\oplus \), 1.49 \( R_\oplus \), and 1.58 \( R_\oplus \) and densities of 8.8, 7.5, and 10.4 g/cm\(^3\), respectively. Thus, it is possible that both Kepler-62e and -62f (with radii of 1.61 \( R_\oplus \) and 1.41 \( R_\oplus \)) are also rocky planets. The albedo and the atmospheric characteristics of these planets are unknown, and therefore the range of equilibrium temperatures (\( T_{\text{eq}} \)) at which the thermal radiation from each planet balances the insolation is large and depends strongly on the composition and circulation of the planets’ atmospheres, their cloud characteristics and coverage, and the planets’ rotation rates (25, 26). However, for completeness, values of \( T_{\text{eq}} \) were computed from \( T_{\text{eq}} = T_{\text{eff}} \left(1 - a_R/(R/2a)^3\right)^{1/4} \), where \( T_{\text{eff}} \) is the effective temperature of the star (4925 K), \( R \) is the radius of the star relative to the Sun (0.64), \( a_R \) is the planet Bond albedo, \( a \) is the planet semimajor axis, and \( \beta \) is a proxy for day-night redistribution (1 = full redistribution, 2 = no redistribution). For the Markov chain Monte Carlo calculations, it was assumed that \( \beta = 1 \) and that \( a_R \) is a random number from 0 to 0.5 (Table 1).

Fig. 1. Kepler-62 light curves after the data were detrended to remove the stellar variability. Plots of the secondary transit light curves (dots), data binned in 0.5-hour intervals (blue error bars), and model fits (colored curves) for Kepler-62b through -62f. Model parameters are provided in Table 1. The error bars get larger as the period becomes larger because there are fewer points to bin together. For the shortest periods, the bars are too small to see.
Gravitational interactions between Kepler-62e and -62f are too weak (9) to cause nonlinear variations in the times of transits (27, 28) and thereby provide estimates of their masses. Nevertheless, upper limits (95th percentile) for Kepler-62e and -62f were derived (table S4): 150 $M_{\oplus}$ and 35 $M_{\oplus}$, respectively. The smallest upper limit to the mass of Kepler-62e based on RV observations (table S4) gives 36 $M_{\oplus}$. These values confirm their planetary nature without constraining their composition. Despite the lack of a measured mass for Kepler-62e and -62f, the precise knowledge of their radii, combined with estimates of their $T_{eq}$ and the stellar age (~7 billion years), imply that Kepler-62e and -62f have lost their primordial or outgassed hydrogen envelope (29, 30). Therefore, Kepler-62e and -62f are Kepler’s first HZ planets that could plausibly be composed of...
condensable compounds and be solid, either as a dry, rocky super-Earth or composed of a substantial amount of water (most of which would be in a solid phase because of the high internal pressure) surrounding a silicate-iron core.

We do not know whether Kepler-62e and -62f have a rocky composition, an atmosphere, or water. Until we get suitable spectra of their atmosphere, we cannot determine whether they are in fact habitable. With radii of 1.61 and 1.41 \( R_{\oplus} \), respectively, Kepler-62e and -62f are the smallest transiting planets detected by the Kepler mission that orbit within the HZ of any star other than the Sun.

**References and Notes**

9. See supplementary materials on Science Online.

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**Supplementary Materials**

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Materials and Methods

Supplementary Text

Figs. S1 to S4

Tables S1 to S4

References (S1–S7)

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