Title: An Earth-sized Planet in the Habitable Zone of a Cool Star

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Abstract:

The quest for Earth-like planets represents a major focus of current exoplanet research. While planets that are Earth-sized and smaller have been detected, these planets reside in orbits that are too close to their host star to allow liquid water on their surface. We present the detection of Kepler-186f, a 1.110.14 Earth radius planet that is the outermost of five planets - all roughly Earth-sized - that transit a 0.470.05 $R_\odot$ star. The intensity and spectrum of the star's radiation places Kepler-186f in the stellar habitable zone, implying that if Kepler-186f has an Earth-like atmosphere and H_2O at its surface, then some of this H_2O is likely to be in liquid form.

Main Text:

In recent years we have seen great progress in the search for planets that, like our own, are capable of harboring life. Dozens of known planets orbit within the habitable zone (HZ), the region around a star within which a planet can sustain liquid water on its surface (*1-4*). Most of these HZ planets are gas giants, but a few such as Kepler-62f (*5*) are potentially rocky despite having a larger radius than Earth. Hitherto, the detection of an Earth-sized planet in the habitable zone of a main-sequence star has remained elusive.

Low-mass stars are good targets in the search for habitable worlds. They are less luminous than the Sun so their habitable zones are located closer in (*6*). The shorter orbital period and larger planet-to-star size ratio of a planet in the HZ of a cool star relative to planets orbiting in the HZ of solar-type stars allow for easier transit detections. M-dwarfs, stars with 0.1-0.5 times the mass of the Sun ($M_\odot$), are very abundant, comprising about three quarters of all main sequence stars in our galaxy (*7*). They also evolve very slowly in luminosity, thus their habitable zones remain nearly constant for billions of years.

Kepler-186 (also known as KIC8120608 and KOI-571) is a main-sequence M1-type dwarf star with a temperature of 3788+/-54 K and an iron abundance half that of the Sun (*8* and SOM Section 2). The star was observed by the Kepler spacecraft at near-continuous 29.4-min intervals. Four planets designated Kepler-186b-e, all smaller than 1.5 $R_\oplus$ with orbital periods between 3.9 and 22.4 days, were confirmed with the first two years of data (*9*, *10*). The fifth planet candidate, Kepler-186f which we discuss herein, was detected with an additional year of data.

We compared the observed data to a five planet model with limb-darkened transits (*9*, *11*) allowing for eccentric orbits to estimate the physical properties of Kepler-186f. We used an affine invariant Markov-chain Monte Carlo (MCMC) algorithm (*12*, *13*) to efficiently sample the model parameter posterior distribution. Kepler-186f has an orbital period of 129.9 days and a planet-to-star radius ratio of 0.021. The additional constraint on stellar density from the transit model allowed us to refine the stellar radius that was previously derived by modeling spectroscopic data. Interior models of cool main-sequence stars such as Kepler-186 show systematic differences to empirically measured stellar properties (*14-16*, SOM Section 2). To account for discrepancies between the empirically measured radii and those derived from model isochrones at the measured temperature for Kepler-186, we have added a 10% uncertainty in quadrature to our stellar radius and mass estimate, yielding a final estimate of $R_\star$ = 0.472+/-0.052 and a planet radius of 1.11±0.14 $R_\oplus$ (Fig. 1, Table S2).

The Kepler-186 planets do not induce a detectable reflex motion on the host star or dynamically perturb each other so as to induce substantial non-Keplerian transit ephemerides, both of which can be used to help confirm the planetary nature of Kepler's planet candidates (*17*, *18*). Instead, we used a statistical approach to measure the confidence in the planetary interpretation of each candidate planet (*19*, *20*). We obtained follow-up high-contrast imaging observations using the Keck-II and Gemini-North telescopes (SOM Section 5) to restrict the parameter space of stellar magnitude/separation where a false positive inducing star could reside and mimic a planetary transit. No nearby sources were observed in either the Keck-II or Gemini data; the 5-σ detection limit set the brightness of a false-positive star to be *Kp*=21.9 at 0.5″ from Kepler-186 and 19.5 at 0.2″ where *Kp* is the apparent magnitude of a star in the Kepler bandpass.

The probability of finding a background eclipsing binary or planet hosting star that could mimic a transit in the parameter space not excluded by observations is very low: 0.5% chance relative to the probability that we observe a planet orbiting the target. However, this does not account for the possibility that the planets orbit a fainter bound stellar companion to Kepler-186. Although we have no evidence of any binary companion to the target star, faint unresolved stellar companions to planet host stars do occur (*21*). We constrained the density of the host star from the transit model by assuming that all five planets orbit the same star. The 3-σ upper bound of the marginalized probability density function of stellar density from our MCMC simulation is 11.2 g cm^{-3}. If Kepler-186 and a hypothetical companion co-evolved, the lower limit on the stellar mass and brightness of a companion would be 0.39 $M_\odot$ and *K*p=15.1, respectively.

Given the distance to Kepler-186 of 151±18 pc, a companion would have to be within a projected distance of 4.2 AU from the target to avoid detection via our follow-up observations. However, a star closer than 1.4 AU from the primary would cause planets around the fainter star to become unstable (*22*). The probability of finding an interloping star with the specific parameters needed to masquerade as a transiting planet is very small relative to the a priori probability that the planets orbit Kepler-186 (<0.02%). Therefore we are confident that all five planets orbit Kepler-186.

While photometry alone does not yield planet masses, we used planetary thermal evolution models to constrain the composition of the Kepler-186 planets. These theories predict that the composition of planets with radii less than about 1.5 $R_\oplus$ are unlikely to be dominated by H/He gas envelopes (*23*). Although a thin H/He envelope around Kepler-186f cannot be entirely ruled out, the planet was likely vulnerable to photo-evaporation early in the star's life when extreme ultra-violet (XUV) flux from the star was significantly higher. Hence any H/He envelope that was accreted would likely have been stripped via hydrodynamic mass loss (*23*). Although Kepler-186f likely does not have a thick H2-rich atmosphere, a degeneracy remains between the relative amounts of iron, silicate rock, and water since the planet could hold on to all of these cosmically-abundant constituents. Mass estimates for Kepler-186f can therefore range from 0.32 $M_\oplus$ if composed of pure water/ice, 3.77 $M_\oplus$ if the planet is pure iron, and an Earth-like composition (about 1/3 iron and 2/3 silicate rock) would give an intermediate mass of 1.44 $M_\oplus$ (Table S3).

For Kepler-186, the conservative estimate of the habitable zone (i.e., likely narrower than the actual annulus of habitable distances) extends from 0.22-0.40 AU (*4*). The four inner planets are too hot to ever enter the habitable zone. Kepler-186f receives 32^{+6}_{-4}% of the intensity of stellar radiation (i.e., insolation) as that received by Earth from the Sun. Despite receiving less energy than the Earth, Kepler-186f is within the habitable zone throughout its orbit (Fig. 2). It is difficult for an Earth-size planet in the habitable zone of an M star to accrete and retain H_2O (*24*, *25*), but being in the outer portion of its star's habitable zone reduces these difficulties.

The high coplanarity of the planets' orbits (given by the fact that they all transit the star) suggest that they formed from a protoplanetary disk. The leading theories for the growth of planets include in-situ accretion of local material in a disk (*26*, *27*), collisional growth of inward-migrating planetary embryos (*28*, *29*), or some combination thereof. We performed a suite of *N*-body simulations of late-stage in situ accretion from a disk of planetary embryos around a star like Kepler-186 (SOM Section 9). We found that a massive initial disk (>10 $M_\oplus$) of solid material with a very steep surface density profile is needed to form planets similar to the Kepler-186 system. Accretion disks with this much mass so close to their star (< 0.4 AU) or with such steep surface density profiles, however, are not commonly observed (*30*), suggesting that the Kepler-186 planets either formed from material that underwent an early phase of inward migration while gas was still present in the disk (*31*) or were somehow perturbed inwards after they formed. Regardless, all simulations produced at least one stable planet in between the orbits of planets e and f, in the range 0.15-0.35 AU (Fig. S5). The presence of a sixth planet orbiting between e and f is not excluded by the observations; if such a planet were to have a modest inclination of a few degrees with respect to the common plane of the other planets we would not observe a transit.

Planets that orbit close to their star are subjected to tidal interactions that can drive the planets to an equilibrium rotational state, typically either a spin-orbit resonance or a "pseudo-synchronous" state whereby the planet co-rotates with the star at its closest approach (*32*, *33*). The proximity of the inner four planets to Kepler-186 suggests that they are likely tidally locked. Kepler-186f, however, is at a large enough distance from the star such that uncertainties in the tidal dissipation function precludes any determination of its rotation rate (*34*). Regardless, tidal locking (or pseudo-synchronous rotation) does not preclude a planet from being habitable. The 5.6 Earth-mass planet GJ 581d (*35*) likely rotates pseudo-synchronously with its star and in addition receives a similar insolation (27%) as Kepler-186f. Detailed climate models have shown GJ 581d to be capable of having liquid water on its surface (*36*, *37*). Taken together, these considerations suggest that the newly discovered planet Kepler-186f is likely to have the properties required to maintain reservoirs of liquid water.

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Fig. 1. The five transiting planet signals observed by Kepler, folded on the orbital periods of the respective planets. The plots are ordered by ascending planet orbital periods. The black points show the observed data and the blue points are the observed data binned in time with one point per phase-folded hour. The most probable transit model is shown in red. The incomplete phase coverage for Kepler-186d is a result of the orbital period of the planet having a value close to an integer multiple of the sampling.

Fig. 2. A schematic diagram of the Kepler-186 system. The upper section of the plot shows a top-down view of the system during a transit of planet f. The relative planet sizes are correct but are not on the same scale as the orbits (shown as black curves). The lower section shows a side-on view comparing Kepler-186 with the solar system (with Earth and Mars in the habitable zone) and the Gliese 581 planets. The stars are located at the left edge of the plot. The dark grey regions represent conservative estimates of the habitable zone while the lighter grey regions are more optimistic extensions of the habitable region around each star (*3*, *4*). Kepler186f receives $0.32^{+0.05}_{-0.04}$ of the incident flux that the Earth receives from the Sun. This puts Kepler-186f comfortably within the conservative HZ, which ranges from 0.25 to 0.88 of Earth's incident flux for this star. Kepler-186f receives a similar incident flux to Gliese 581d (*35*) which has been shown to be capable of hosting liquid water (*36*, *37*).

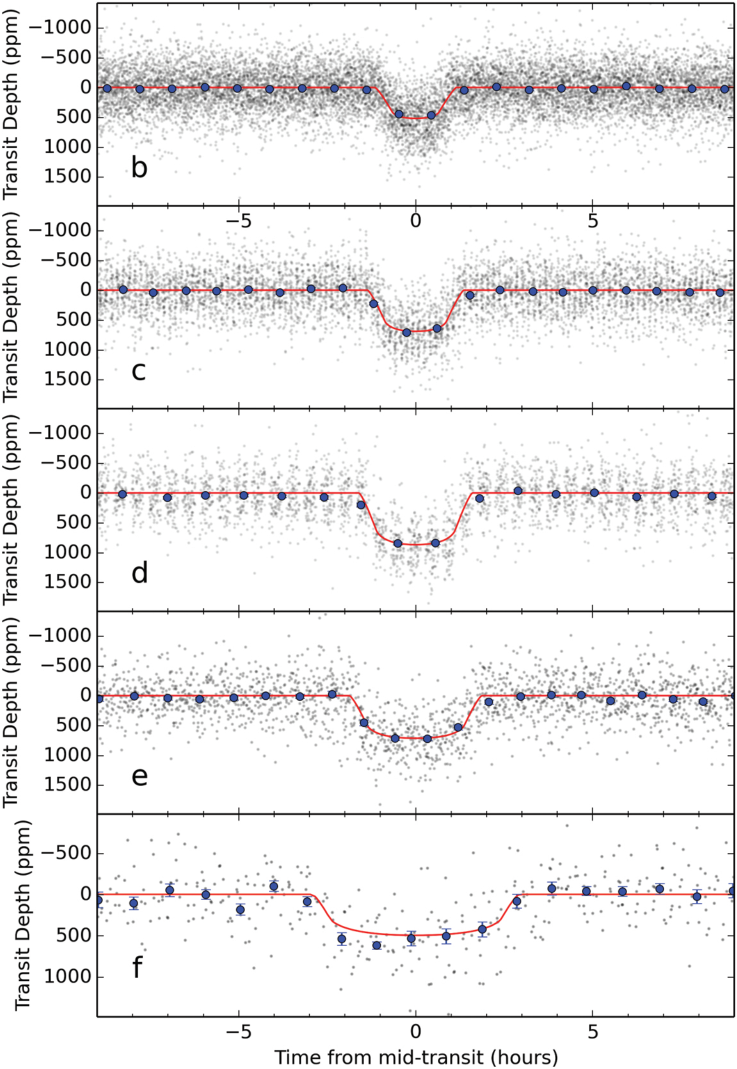
Supplementary Materials:

Materials and Methods

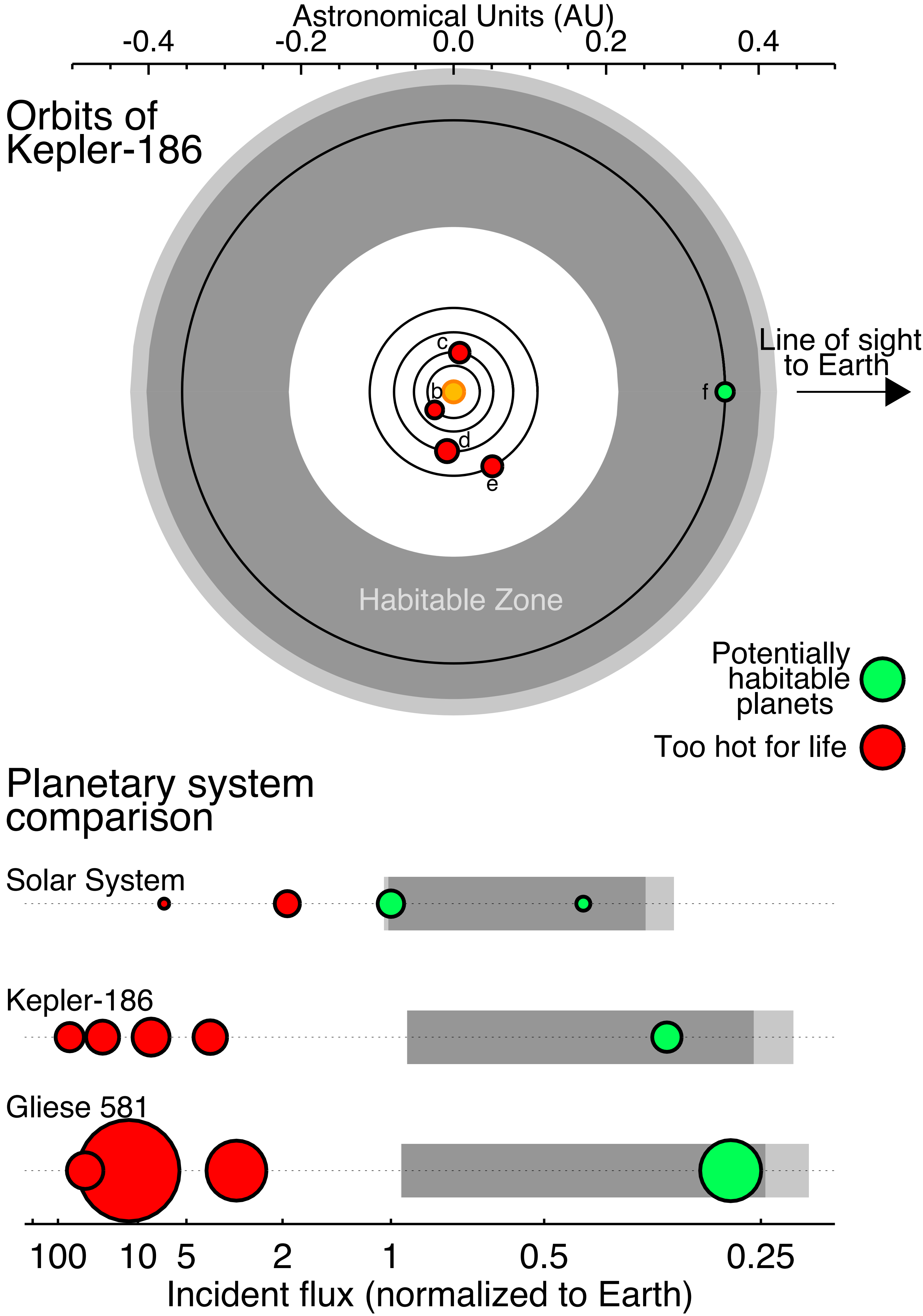
Figures S1-S7

Tables S1-S2

References (*38*-*73*)



Transit Depth (ppm)
−1000
−500
0
500
1000
1500
b
c
d
e
f
−5
0
5
Time from mid-transit (hours)


Astronomical Units (AU)
-0.4
-0.2
0.0
0.2
0.4
Orbits of Kepler-186
c
b
d
e
f
Line of sight to Earth
Habitable Zone
Potentially habitable planets
Too hot for life
Planetary system comparison
Solar System
Kepler-186
Gliese 581
100
10
5
2
1
0.5
0.25
Incident flux (normalized to Earth)