The Impact of Stellar Distances on Habitable Zone Planets

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Abstract
Among the most highly valued of exoplanetary discoveries are those of terrestrial planets found to reside within the habitable zone (HZ) of the host star. In particular, those HZ planets with relatively bright host stars will serve as priority targets for characterization observations, such as those involving mass determinations, transmission spectroscopy, and direct imaging. The properties of the star are greatly affected by the distance measurement to the star, and subsequent changes to the luminosity result in revisions to the extent of the HZ and the properties of the planet. This is particularly relevant in the realm of Gaia, which has released updated stellar parallaxes for the known exoplanet host stars. Here we provide a generalized formulation of the effect of distance on planetary system properties, including the HZ. We apply this methodology to three known systems and show that the recent Gaia Data Release 2 distances have a modest effect for TRAPPIST-1 but a relatively severe effect for Kepler-186 and LHS 1140.

Key words: planetary systems – stars: individual (Kepler-186) – techniques: photometric

1. Introduction
At the present time, the vast majority of exoplanets have been detected via indirect methods, most particularly through the transit and radial velocity (RV) methods. The derived properties of the planet and the surrounding environment are thus highly dependent upon the ability to accurately constrain the host star parameters. As such, there has been a concerted effort to maximize the precision of stellar properties (e.g., Huber et al. 2014; Boyajian et al. 2015; Sandford & Kipping 2017, and references therein). A major impediment to constructing a self-consistent stellar model for a given star is poor distance estimates since the calculated intrinsic luminosity of the star is tied to distance and flux measurements. Fortunately, missions such as Hipparcos (van Leeuwen 2007) and Gaia (Prusti et al. 2016) have dramatically improved our knowledge of stellar distances and provided subsequent improvements to stellar property estimates. In particular, the distances from Gaia Data Release 2 (DR2; Brown et al. 2016) have already had an enormous impact on estimates of stellar properties (Van Grootel et al. 2018), such as those derived for the Kepler host stars by Berger et al. (2018).

As well as alterations to the fundamental properties of the star and planet, a change in distance to a planetary system also alters the system flux environment since that depends on the measured stellar luminosity. In that regard, the greatest impact is on the boundaries of the habitable zone (HZ) and can determine if planets lie inside or outside of that region. The HZ is described in detail by Kasting et al. (1993), Kopparapu et al. (2013), Kasting et al. (2014), and Kopparapu et al. (2014), is graphically illustrated by the Habitable Zone Gallery (Kane & Gelino 2012a), and was utilized to create a catalog of Kepler candidates that reside in the Habitable Zone (Kane et al. 2016). In these previous works, the boundaries of the HZ are divided into two major categories. The “conservative” HZ (CHZ) uses the runaway greenhouse and maximum CO₂ greenhouse criteria to delimit the boundaries of the region. The “optimistic” HZ (OHZ) extends the width of the HZ by accounting for best-case scenarios whereby Venus and Mars could have retained liquid surface water. The circumstellar CHZ and OHZ boundaries are primarily determined as a function of the luminosity and effective temperature of the host star, the accuracy of which is paramount for assessing the number of HZ planets and calculations of n-Earth (Kane 2014).

In this Letter, we provide a methodology for determining the impact of a change in a star’s measured distance on the planetary system properties including those of the star, planet, and the HZ. The methodology is derived and quantified in Section 2 together with a demonstration of relative changes in the various system parameters. These relationships are applied to several case studies in Section 3, including the TRAPPIST-1, Kepler-186, and LHS 1140 planetary systems. We discuss additional caveats related to changes in distance measurements that need to be considered in Section 4 and conclude in Section 5 with implications of the methodology for other systems.

2. How New Distances Change System Parameters
We start with the impact of stellar distance on the stellar luminosity. The relationship between stellar distance and incident flux, F, is given by

\[ F = \frac{L_*}{4\pi d_*^2}, \]

where \( L_* \) is the stellar luminosity and \( d_* \) is the distance from the observer to the star. For a given flux received at Earth, the fractional change in luminosity caused by a revised distance of \( d_* \) is given by

\[ \frac{\Delta L_*}{L_*} = \left( \frac{d_*'}{d_*} \right)^2 - 1. \]

The luminosity of the star is determined via the Stefan–Boltzmann law applied to stars

\[ L_* = 4\pi R_*^2 \sigma T_{\text{eff}}^4, \]

where \( R_* \) is the stellar radius and \( T_{\text{eff}} \) is its effective temperature. Assuming a \( T_{\text{eff}} \) that is unaffected by stellar distance (such as extraction from spectral analysis), then the
This relationship applies to both the CHZ and OHZ boundaries.

Based on a revised luminosity from Equation (2), \( L'_* \), the fractional change in stellar radius is given by

\[
\frac{\Delta R_*}{R_*} = \frac{\sqrt{L'_*} - \sqrt{L_*}}{\sqrt{L_*}} = \sqrt{\frac{L'_*}{L_*}} - 1.
\]

(5)

The consequence of this change in stellar radius on planetary radius, \( R_p \), is determined from its relationship to transit depth

\[
\Delta F = \left(\frac{R_p}{R_*}\right)^2,
\]

(6)

which is a measurement that does not depend on stellar distance. The fractional change in planet radius is then

\[
\frac{\Delta R_p}{R_p} = \frac{\Delta R_*}{R_*}.
\]

(7)

A more dramatic change occurs with the planetary bulk density since \( \rho_p \propto R_p^{-3} \), leading to a fractional change in density of

\[
\frac{\Delta \rho_p}{\rho_p} = \left(\frac{R'_p}{R_p}\right)^{-3} - 1,
\]

(8)

where \( R'_p \) is the revised planetary radius.

As seen in Equation (1), the flux is linearly proportional to the stellar luminosity. Therefore, the fractional change in flux received by the planet is

\[
\frac{\Delta F_p}{F_p} = \frac{\Delta L_*}{L_*}.
\]

(9)

The effect of the change in stellar parameters on the HZ is derived using the polynomial relations described in Kopparapu et al. (2013, 2014). Specifically, the HZ distance, \( d \), is specified by

\[
d_{HZ} = \left(\frac{L_*}{S_{eff}}\right)^{0.5} \text{ au},
\]

(10)

where the stellar flux, \( S_{eff} \), is given by

\[
S_{eff} = S_{eff\odot} + c_1 T_e + c_2 T_e^2 + c_3 T_e^3 + c_4 T_e^4
\]

(11)

and \( T_e = T_{eff} = 5780 \) K. The polynomial coefficients for the CHZ and OHZ can be found in Kopparapu et al. (2014). Based on Equation (10), the HZ distances have an identical proportionality, as with \( R_* \), to \( \sqrt{L_*} \). The fractional change in the HZ boundaries is then

\[
\frac{\Delta d}{d} = \sqrt{\frac{L'_*}{L_*}} - 1 = \frac{\Delta R_*}{R_*}.
\]

(12)

This relationship applies to both the CHZ and OHZ boundaries.

The various effects described in this section are summarized in the plot shown in Figure 1, which displays the dependencies of system parameters on the distance ratio, \( d'/d_* \). The solid line represents the quadratic relationship of \( L_* \) and \( F_p \) on the distance ratio. The dashed line represents the linear relationship of \( R_* \) and \( d \) on the distance ratio. The dotted line represents the cubic relationship of \( \rho_p \) on the distance ratio. Note that, with the exception of density, the structure of the equations presented here results in a positive fractional change in parameters if the distance increases and a negative fractional change if the distance decreases.

3. Case Studies of Known HZ Systems

In this section, we examine three specific systems that are well known for their HZ planets: TRAPPIST-1, Kepler-186, and LHS 1140. Specifically, we utilize the revised distances from the Gaia DR2 to re-evaluate the properties of these systems.

3.1. TRAPPIST-1

The TRAPPIST-1 planetary system was first discovered to harbor three planets by Gillon et al. (2016), with an additional four found later (Gillon et al. 2017). K2 observations were used to both confirm and verify the orbital period of the outer planet (Luger et al. 2017). The primary source of interest in the system is due to three of the planets residing within the HZ of the host star (Bolmont et al. 2017). Mass determinations for the planets were achieved by Grimm et al. (2018) using Transit Timing Variations (TTVs) leading to greatly improved density estimates. Furthermore, the density estimates have been used to model the atmospheres and interiors, leading to conclusions such as that of Wolf (2017) that planet e has the highest likelihood of liquid surface water, and the estimates of volatile budgets by Unterborn et al. (2018). These modeling efforts are further complicated by the potential for significant atmospheric mass loss due to the relatively high XUV radiation environment created by the activity of the host star (Roettenbacher & Kane 2017; Wheatley et al. 2017). The relative closeness of the TRAPPIST-1 system combined with the intrinsic scientific value of the terrestrial planets make follow-up observations of the system highly likely.

Prior to DR2 becoming available, the properties of the TRAPPIST-1 host star were known as \( d_*=12.14 \pm 0.12 \text{ pc}, \) \( T_{eff} = 2516 \pm 41 \text{ K}, \) \( L_* = 0.000522 \pm 0.000019 L_\odot, \) and \( R_* = 0.121 \pm 0.003 R_\odot \) (Van Grootel et al. 2018). DR2 provides a new parallax for TRAPPIST-1 of \( \rho = 80.4512 \pm 0.1211 \text{ mas}, \)
which corresponds to a revised distance \( d_* = 12.43 \pm 0.02 \) pcs. Using the methodology in Section 2, the luminosity has increased by 5.5\% \( (L_* = 0.000551 \pm 0.0000019 \, L_\odot) \) and the stellar radius has increased by 2.7\% \( (R_* = 0.124 \pm 0.003 \, R_\odot). \)

The consequences of the revised stellar parameters for TRAPPIST-1 are that the planetary radii increase by 2.7\%, the bulk densities decrease by 7.7\%. The planetary masses remain unaffected in this case since they were determined via TTVs. Table 1 summarizes the fractional change in the system properties for all three case study systems as a result of the DR2 distance revisions. The changes are demonstrated graphically in Figure 2, which shows the planetary radii and the location of the HZ boundaries (light green is the CHZ, dark green is the OHZ) for the old distance and for the newly revised distances. The HZ planets of the TRAPPIST-1 system retain their status as HZ planets when accounting for the new stellar distance.

The reduction in bulk density of the planets has profound consequences for their volatile inventory. Unterborn et al. (2018) argue that the relatively low densities of the \( f \) and \( g \) planets are best explained by formation beyond the snow line and subsequent migration. They further determine that a water-rich environment with no continents will lead to a suppression of biosignatures due to the relative lack of geochemical cycles involving, for example, carbon and phosphorus. The decrease in density implies that the volatile content of the TRAPPIST-1 planets is even higher than previously thought, and indicates that a reanalysis of the planetary interiors should be considered to properly evaluate their potential for observations involving biosignatures.

### 3.2. Kepler-186

The Kepler-186 system was first validated as a confirmed planetary system due to its multoplanet nature (Lissauer et al. 2014; Rowe et al. 2014), at which time it was known to contain four planets. The fifth planet was detected and confirmed by Quintana et al. (2014), and generated considerable interest due to its radius of only 1.11 \( R_\oplus \) and its location in the HZ of the host star. At that time, Kepler-186 \( f \) was considered to be the most “Earth-like” in terms of size and insolation flux, leading to models of the possible energy budgets and habitability potential (Bolmont et al. 2014).

The stellar parameters for Kepler-186 were described by Quintana et al. (2014) as follows: \( d_* = 151 \pm 18 \) pcs, \( T_{\text{eff}} = 3788 \pm 54 \, \text{K}, \) \( L_* = 0.0412 \pm 0.0090 \, L_\odot, \) and \( R_* = 0.472 \pm 0.052 \, R_\odot. \) The DR2 parallax of \( p = 5.6020 \pm 0.0243 \) mas equates to a revised distance of \( d_* = 177.51 \pm 0.79 \) pcs. The new distance translates in a luminosity increase of 38.2\% \( (L_* = 0.0569 \pm 0.0090 \, L_\odot) \) and a stellar radius increase of 17.6\% \( (R_* = 0.555 \pm 0.052 \, R_\odot). \) A refit of the stellar parameters of Kepler host stars by Berger et al. (2018) used DR2 distances and included an isochrone fitting methodology that produced a revised effective temperature and stellar radius of \( T_{\text{eff}} = 3748 \pm 75 \, \text{K} \) and \( R_* = 0.56 \pm 0.02 \, R_\odot \) respectively.

Thus, the stellar radius derived in this work is in close agreement with the radius derived by Berger et al. (2018).

The 17.6\% increase in stellar radius also raises the radius of planet \( f \) to 1.31 \( R_\oplus. \) This likely means that the planet is still within the terrestrial regime (Chen & Kipping 2017), although it is more comparable to a super-Earth than a true Earth analog.

The mass of the planet has not been reliably measured due to the lack of detectable TTV or RV signals, thus the true impact on the bulk density of the planet is unknown. For a constant mass, the density would decrease by 38.5\%, so this may be considered an upper limit to the density drop. The HZ boundaries also increase by 17.6\%, which is a significant change in the radiation environment of the system. Fortunately, planet \( f \) was previously located at the outer edge of the CHZ and so the planet has changed from an Earth-size planet at the HZ outer edge to a super-Earth in the middle of the HZ (see the second row of Figure 2). The modifications to the Kepler-186 system are summarized in Table 1.

### 3.3. LHS 1140

The planet orbiting LHS 1140 was discovered by Dittmann et al. (2017) and determined to be a rocky super-Earth in the HZ of the host star. The transit data yielded a radius of 1.43 \( R_\oplus \) and the RV data yielded a mass of 6.65 \( M_\oplus \), the combination of which yields a bulk density of 12.5 \( g \, \text{cm}^{-3}. \) As for the TRAPPIST-1 system, the relative proximity of LHS 1140 and the interest in the planet ensure that the system will be a valued target for follow-up observations designed to characterize the atmosphere (Checlair et al. 2017).

The stellar parameters provided by Dittmann et al. (2017) are \( d_* = 12.47 \pm 0.42 \) pcs, \( T_{\text{eff}} = 3131 \pm 100 \, \text{K}, \) \( L_* = 0.002981 \pm 0.000021 \, L_\odot, \) and \( R_* = 0.186 \pm 0.013 \, R_\odot. \) The DR2 parallax of \( p = 66.6996 \pm 0.0674 \) mas, which translates into a revised distance of \( d_* = 14.993 \pm 0.016 \) pcs. The increase in stellar distance has the dramatic effect of increasing the luminosity by 44\% \( (L_* = 0.004293 \pm 0.000021 \, L_\odot) \) and the stellar radius by 20\% \( (R_* = 0.223 \pm 0.013 \, R_\odot). \)

The update to the stellar parameters for LHS 1140 results in an increased planetary radius of 1.72 \( R_\oplus. \) Normally such a planetary size would indicate that the planet is not rocky (Rogers 2015) and is more likely to fall into the mini-Neptune category. Assuming the mass of the planet is unchanged, the reduction in bulk density is 42.1\%, resulting in a revised density of \( \rho = 8.8 \, g \, \text{cm}^{-3}. \) The revised density indicates that either the planet is an exceptionally large super-Earth or that it is a mini-Neptune with a heavy core. Furthermore, the increase of 20\% in the HZ boundaries pushes the planet to the near-side of the CHZ. The third row of Figure 2 demonstrates the dramatic change to the properties of the planet. The modifications to the LHS 1140 system are summarized in Table 1.
4. Discussion

The scaling laws presented here for modifying the stellar and planetary parameters provide a first-order estimate of the expected changes. However, a more thorough approach will utilize an isochrone fitting methodology, making use of isochrones such as those compiled in the “Dartmouth Stellar Evolution Database” (Dotter et al. 2008). This is particularly important because an isochrone refitting of the stellar parameters will likely result in a new value for the stellar mass. Stassun et al. (2017, 2018) suggest that the masses of host stars can also be determined through a combination of Gaia parallaxes and precision photometry that leads to a measurement of stellar surface gravity. If a revised mass measurement for a star is found to have increased from
previous measurements, there will be several consequences for
the associated planets, such as increasing the semimajor axis
for a given orbital period, and increasing planetary masses that
are determined using the RV method. Such changes could help
to mitigate decreases to the planetary bulk density and
increases to the incident flux on the planet due to the increased
stellar luminosity.

It should be noted that changes to the stellar luminosity are
not the only factors that affect the habitability of planets within
the HZ. The intrinsic properties of the planet are a critical
aspect of assessing the potential surface conditions, and indeed
the extent of the HZ can be altered by a range of atmospheric
accuracy changes processes and relationships to geophysical
cycles (Abbot 2016; Haqq-Misra et al. 2016, 2018; Kopparapu
et al. 2017; Ramirez & Kaltenegger 2017, 2018) as well as
planetary rotation rates (Yang et al. 2014; Leconte et al. 2015;
Kopparapu et al. 2016). The orbital properties of the planet also
play an important role in the atmospheric dynamics and surface
conditions, such as the orbital eccentricity (Williams & Pollard
2002; Kane & Gelino 2012b). The scaling laws
presented in Section 2 do not directly affect these planetary
properties with the exception of how changes in planetary
density can influence surface gravity and atmospheric scale
height.

As seen in Section 3, the overall effect of changes in stellar
distance for known HZ planets can vary substantially without an
obvious dependence on distance. Kepler-186 has a large
correction for the distance that is not unexpected given that the
star is relatively far away. However, TRAPPIST-1 and LHS 1140 have dramatically different alterations to their
distances and system properties, despite the fact that they are
both relatively close. The explanation for this is that the
TRAPPIST-1 system has been known for longer and has been
studied in much greater detail than the LHS 1140 star, and thus
the overall properties of the star, including distance, have been
better characterized.

5. Conclusions

Although the dependence of planetary properties on stellar
parameters is well known, the consequences of changing the
stellar distance are less often considered. As demonstrated here,
the transition from poorly to accurately constrained stellar
distances can have a serious impact on planetary properties.
This is especially important for those targets that are expected
to form the core sample of expensive follow-up observations that
to attempt atmospheric characterization and those planets that
become the subject of detailed climate modeling simulations.

Perhaps the most important planetary property that changes
as a result of stellar distance is the bulk density. For terrestrial
planets in the HZ, the density together with stellar abundances
has become a key diagnostic in modeling planetary interiors
and potential volatile content (Hinkel & Unterborn 2018).
For the analysis of the TRAPPIST-1 system (Section 3.1) the
overall changes to the system are moderate, but the decrease in
the planetary bulk densities is relatively large, indicating that the
planets f and g may indeed be aqua-planets with no
continents, and planet e may also fall into this category. The
largest effect was for LHS 1140b, whose density plummets
while the received flux dramatically increases. Such changes to
these planets will have a significant effect on the surface
gravity, atmospheric scale height, and therefore the feasibility
of transmission spectroscopy observations (Morley et al. 2017;
Batalha et al. 2018). Thus, as distances are further improved
through Gaia data releases, the target list to be studied with
precious observing resources will become increasingly robust.

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