THE MEAN GLOBAL SURFACE TEMPERATURE OF EXOPLANETS. Abel Méndez¹, Ramses Ramirez², and Edgar Rivera-Valentin³. ¹Planetary Habitability Laboratory, University of Puerto Rico at Arecibo, Arecibo, PR, USA (abel.mendez@upr.edu). ²Earth-Life Science Institute, Tokyo, Japan (rramirez@elsi.jp). ³Lunar and Planetary Institute, USRA, Texas, USA (ervalentin@usra.edu).

Introduction: Surface temperature is one of many factors controlling the climate, weathering rates, and habitability of planets [1]. It is determined by a complex interaction of surface and atmospheric properties fed by some energy source. This energy can come from the parent star radiation (i.e., stellar flux) or the tidal interaction with other planetary or stellar objects [2, 3]. The internal energy and radioactive decay can also contribute to the thermal state of the planet, but not for many billions of years [4]. Other more exotic energies, such as the cosmic microwave background and dark matter, might contribute to stable surface temperatures [5, 6].

Unfortunately, surface temperature is not currently measurable for any known exoplanet. Theoretical attempts to explore these temperatures use simple energy balance models to computational demanding General Circulation Models (GCMs). These are generally limited by the range of planetary conditions that they can recreate, often limiting to conditions more similar to Earth. Surface temperatures, though, depend on the equilibrium temperature and the greenhouse effect of the planets. The normalized greenhouse $G_n$ connects the equilibrium and surface temperatures as

$$T_s = k T_{eq}$$

![Figure 1](0x0). Mean global surface temperature of planets as function of stellar flux. Square and circles correspond to published modeled planets from 1D to 3D models and the Solar System (magenta circles). General curves for different $\kappa$ factors are shown (dotted green lines). Earth-like planets have atmospheres with $\kappa \approx 1$ while those with dense atmospheres (> 10 bars) have $\kappa > 1.5$. 
where $G$ is the greenhouse effect or forcing (usually measure in W/m$^2$), and $T_e$ is the surface temperature [7].

Both the bond albedo and the normalized greenhouse are convenient quantities to summarize complex surface and atmospheric properties in a zero to one scale. The surface temperature of a planet is then given by

$$T_s = \kappa T_{eq0}$$

where $T_{eq0}$ is equilibrium temperature of the planet for zero bond albedo, $\kappa = \frac{1-A_b}{1-G_0}$, and $A_b$ is the bond albedo of the planet. Here $\kappa$ depends not only in the combined surface and atmospheric properties of the planet but also in the stellar flux and spectrum of the star. It is also possible to estimate the mean subsolar and polar temperatures depending on the atmospheric convection of the planet.

**Methodology:** Here we use first principles to create a general analytical model to constrain the mean global surface temperature of rocky planets with thin to dense atmospheres. Our model is validated with the Solar System and many 1D to 3D GCM simulations such as ROCKE-3D, among others [8, 9, 10, 11, 12]. We explored the parameter space of surface temperatures with a Monte Carlo simulation using a zero dimensional model based on equation 2. From the simulations we calculated the probability density function, expected values, and confidence levels of $\kappa$ for potential planetary scenarios.

We started by assuming that the bond albedo $A_b$ and normalized greenhouse $G_0$ of planets were independent quantities uniformly distributed. This is not necessarily true since the bond albedo includes the absorption and reflecting qualities of both the surface and the atmosphere, and the normalized greenhouse also depends on the incoming and reflected flux. Our simulations address all possible scenarios, including some not necessarily represented in nature. Thus, we corrected and validated or model using data from our own Solar System and many 1D to 3D climate models simulations. The albedo and greenhouse were parameterized as function of other stellar or planetary properties.

**Conclusion:** We found relations for the expected temperatures of rocky to ocean worlds around Sun-like to M-dwarfs stars. In general, the surface temperatures of these planets are close to $T_s \approx T_{eq0}$ where $T_{eq0}$ is the equilibrium temperature for zero bond albedo. For example, the mean global surface temperature for bodies with low density atmospheres (i.e., <10 bars) around any type of star is (90% confidence level)

$$T_s = \frac{0.984 \pm 0.173}{T_{eq0}}.$$ 

Planets with denser atmospheres above 10 bars have $\kappa > 1.5$ (see figure 1). The surface temperature for Earth-like planets with one bar atmospheres around Sun-like stars can be further constrained to

$$T_s = \frac{1.040 \pm 0.056}{T_{eq0}}.$$ 

For example, equation 4 predicts a surface temperature of 290 ± 16 K for Earth ($T_{eq0} = 278.5$ K) where the actual value is 288 K. In general, planets in elliptical orbits will have lower temperatures than those in circular orbits [13]. The difference and uncertainty between surface and equilibrium temperature increase with stellar flux. Both Earth and Titan have similar greenhouse effects, but at Earth's orbit this represents 33 K difference while only 10 K at Titan's orbit, with respect to their equilibrium temperatures. Therefore, it is easier to estimate the temperature of cold planets than hot ones.

It is theoretically possible for a planet with a stellar flux between one-tenth to ten times the terrestrial value to have temperate conditions. However, those similar to Earth are more restricted to stellar fluxes between 0.6 to 2 times the terrestrial value. Thus, we define the Temperate Zone (TZ) as the region around a star where a planet with similar albedo and greenhouse as Earth would have a non-zero probability of a temperate surface (i.e., 0° to 50°C). This zone overlaps parts of the empirical habitable zone and helps to identify exoplanets that are more likely to be more thermally similar to Earth, although not necessarily with the same amount of water. It is then expected that any exoplanet biosignature is correlated with the Temperate Zone.

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