Estimating the Distribution of Habitable Surface Area in the Milky Way

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Motivation and goals

- We are starting to discover a rich diversity of exoplanets. Our Galaxy may contain at least 3 different types of habitable worlds
  - Earth analogues, i.e. rocky planets in the conventional habitable zone
  - Tidally locked planets with a habitable band
  - Jovian moons that are beyond the ice line but are tidally heated, like Europa
  - How important is each type of world? How is the total habitable surface area distributed amongst the different types of worlds and different types of stars?
- With ever-improving statistics on small planets, we can now begin to estimate not only the number of habitable planets, but also their distribution among different stars and planet sizes and types.
- **Goals of this work**
  - Take a step towards quantifying the distribution of habitable surface area in the Galaxy across different kinds of planets and stars
  - Gain a better understanding of the interplay of some key factors and how they relate to habitability.

General Approach

- Effects considered:
  - Maximum number of planets for dynamically packed systems (Heng and Tremaine 2009)
  - Statistics from February 2011 Kepler data release (Borucki et. al. 2011, Howard et. al. 2011)
  - Planetary mass function (based on combination of Heng and Tremaine 2009 and O'Toole et. al. 2009)
  - Stellar mass function (Kroupa et. al. 2002)
  - Stellar mass-luminosity relationship
  - Habitable zone limits for the "Earth analogue" branch (Kasting et. al. 1993)
  - Total mass in Jovian moons (Canup and Ward 2006)
  - Rocky planet mass-radius relationship (Seager et. al. 2007)
  - Tidal locking radius based on time to tidal lock of 10Gy
- Effects ignored:
  - Stellar activity
  - Atmospheric transport
  - Greenhouse effect
  - Axial tilt stabilization
  - Bombardment
  - Galactic habitable area
  - Planetary chemistry

For each of the 3 planet types, we define the distribution of the habitable real estate in the galaxy as

$$\frac{\partial^2 A_{tot}(m,M_*)}{\partial m \partial M_*} = \frac{dN(M_*)}{dM_*}\int_{a_{\min}(m,M_*)}^{a_{\max}(m,M_*)} A(m,M_*,a)\frac{\partial^2 n(m,a;M_*)}{\partial m \partial a}da$$

where :

- m, M_*, a are planet mass, star mass, and orbital semi-major axis
- dN/dM is the stellar mass function, normalized to the total number of stars in the galaxy, which we take to be10^{10}
- a_{min}, a_{max} are the boundaries of the habitable zone for each type of planet
- $A(m,M_*, a)$ is the area of a planet of mass m, at a distance R around a star of mass M_*
- $\frac{\partial^2 n(m,a;M_*)}{\partial m \partial a}$ is the distribution of the number of planets around a star of mass M_*. We estimate it in the next section

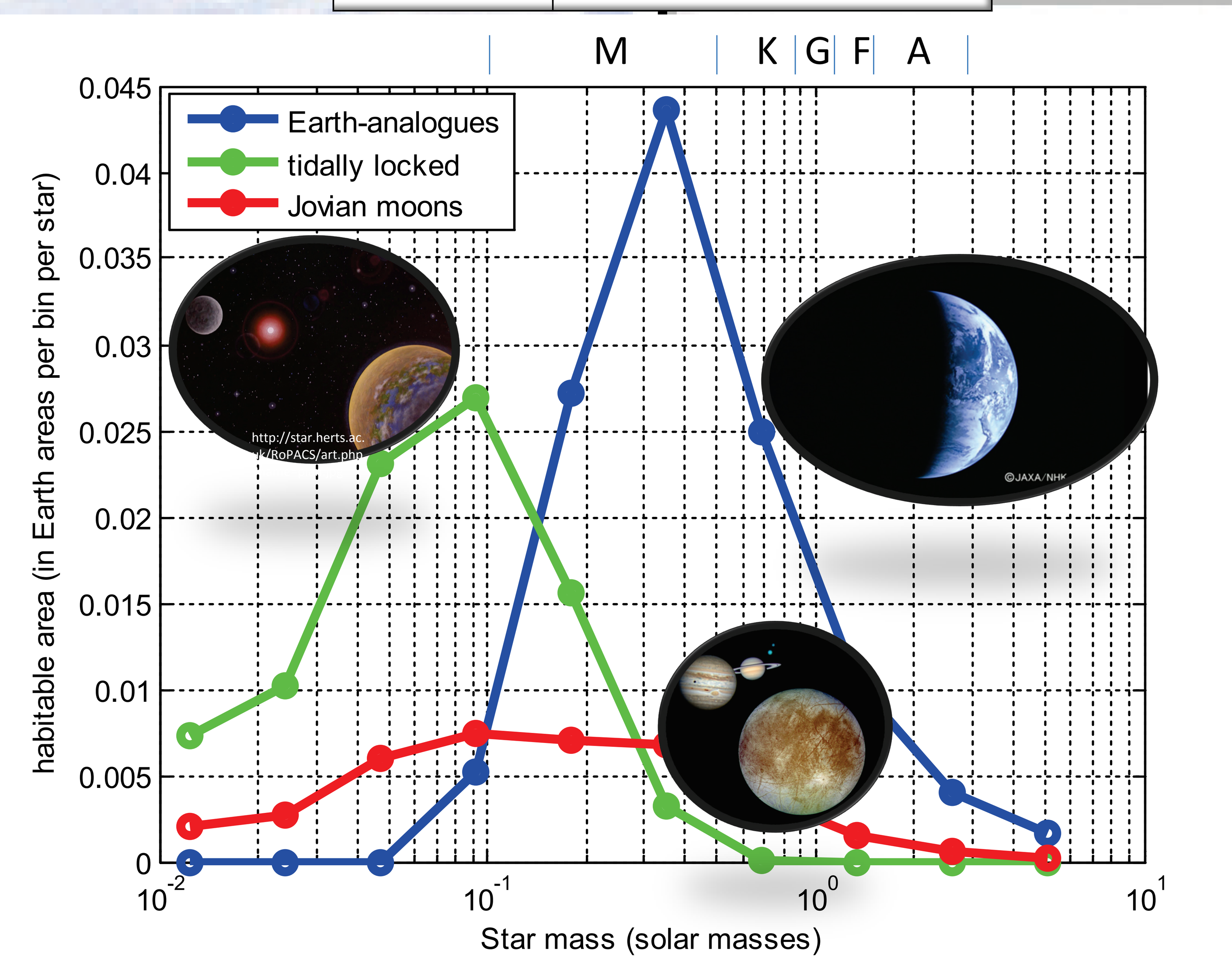
We used the following values for the three planet types (or branches):

Branch	$a_{max}(m, M_*)$	$a_{min}(m, M_*)$	$A(m, M_*, a)$
Earth analogues	$1.37a_\oplus\sqrt{\frac{L_*(M_*)}{L_\odot}}$	$max\begin{cases}0.95a_\oplus\sqrt{\frac{L_*(M_*)}{L_\odot}}\\ a_{TL}(m,M_*)\end{cases}$	$4\pi r^2(m)$
Tidally-locked	$min\begin{cases}\sqrt{\frac{0.7L_*(M_*)}{4\pi\sigma T^4_{low}}}\\ a_{TL}(m,M_*)\end{cases}$	$0.25\sqrt{\frac{0.7L_*(M_*)}{4\pi\sigma T^4_{low}}}$	$\frac{8\pi^2 r^2(m)a^2\sigma}{L_*(M_*)}(T^4_{high}-T^4_{low})$
Jovian moons	$100a_{min}(m,M_*)$	$a_\oplus\sqrt{\frac{L_*(M_*)}{L_\odot}}$	$A_{Europa}\frac{m}{m_{Jupiter}}$

where:

- a_{TL} is the tidal-lock radius after 10 Gy for an average silicate planet
- The habitable surface of a tidally locked planet is defined as where the temperature is between 0 and 100C assuming that the planet absorbs 0.7 of starlight
- The moons of Jovians were assumed to be all of Europa size, with their total mass taken as 1e-4 of the host planet's mass per Canup and Ward 2006
- The range of semi-major axes for the Jovians was assumed as approximately the iceline and 100 times the iceline.

Branch	Estimate of mean habitable surface area per star
Earth-analogues	~ 0.12
Tidally locked	~ 0.09
Jovian moons	~ 0.04
Total	0.25 (1 Earth area per 4 stars)



Combining latest Kepler statistics with dynamical packing

- We use two main ingredients to derive the planet distribution n around a given star: the dynamically packed hypothesis and Kepler statistics. DP guides the extrapolation both to long periods and to other stars
- We make the following assumptions within the semimajor axis range of interest:
  - A given star's planets are all the same "dominant mass" m
  - The probability distribution of dominant mass $p(m)$ is the same for all stars, with smallest mass being 0.1 m_{Earth}
  - All planetary systems are within a constant "packing factor" η of being dynamically packed
  - Dynamically packed distribution of planets then can be written as

$$\frac{\partial^2 n(m,a;M_*)}{\partial \log m\, \partial \log a} = \frac{\eta \ln 10}{4}\left(\frac{M_*}{m}\right)^{0.3} p(m)$$

  - This is independent of a (or equivalently, period), which is consistent with Kepler for long periods and motivates extrapolating the Kepler results for larger periods or semi-major axes as a flat line (see figure)
  - It also defines how the distribution varies with different stars
- On the other hand, analysis of Kepler data leads to (following Howard et. al. 2011)

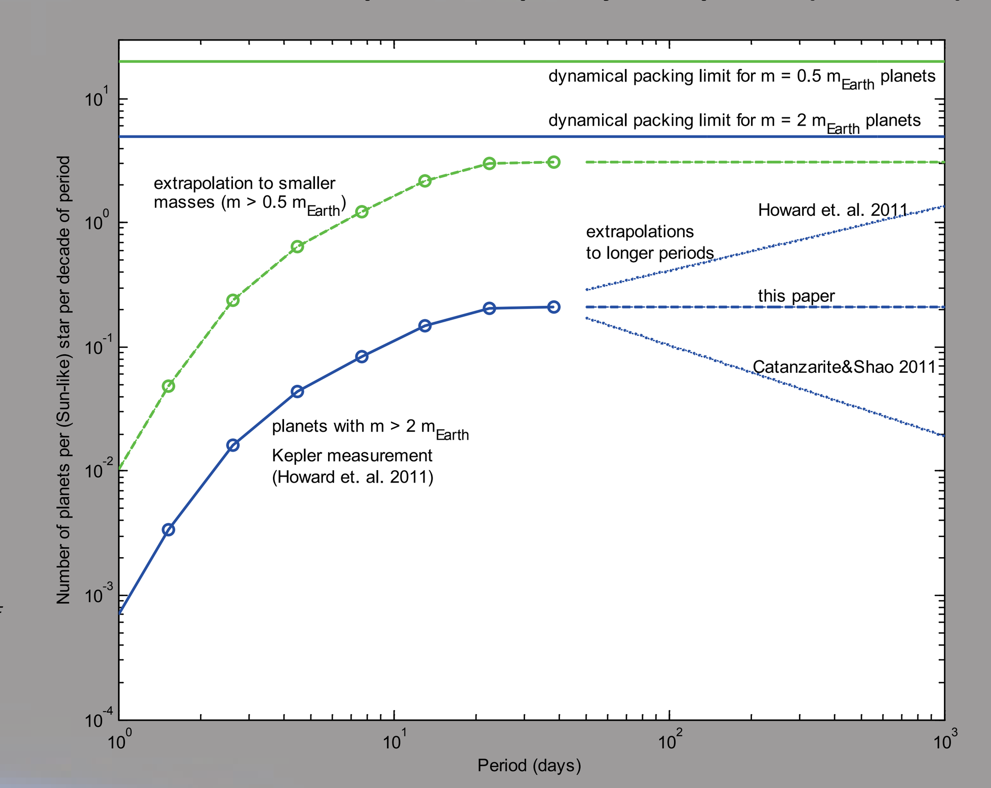
$$\frac{\partial n(m,a;M_{Sun})}{\partial \log a} = 0.87 m^{-0.58}$$

  - Comparing the two equations allows to solve for $p(m)$ as well as η = 0.15, and finally obtain

$$\frac{\partial n(m,a;M_*)}{\partial \log a\, \partial \log m} = 1.4\left(\frac{M_*}{M_{Sun}}\right)^{0.3} m^{-0.58}$$

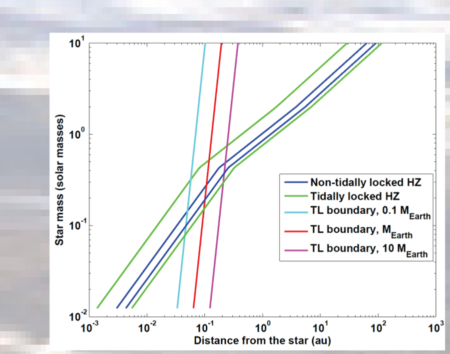
which now fully specifies the formula for A_{tot}

Different models of planet frequency with period (or SMA a)

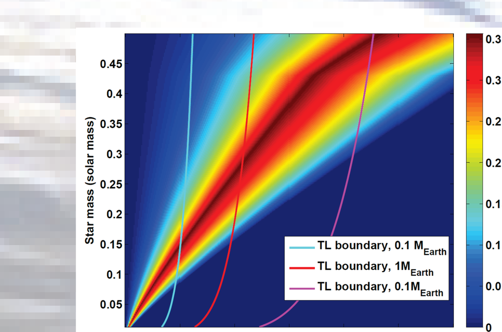


Results

Effects of tidal locking

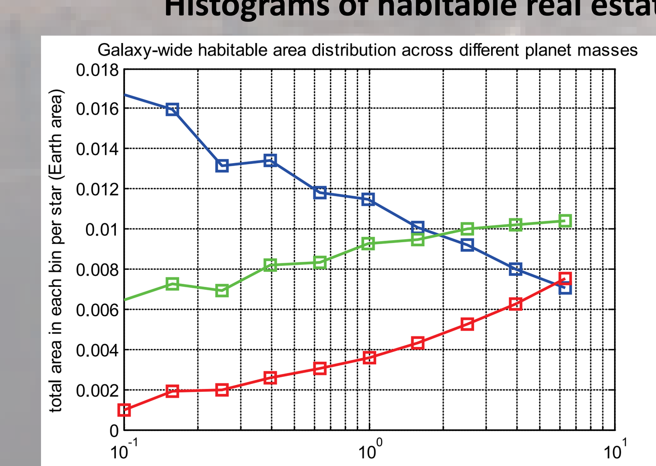


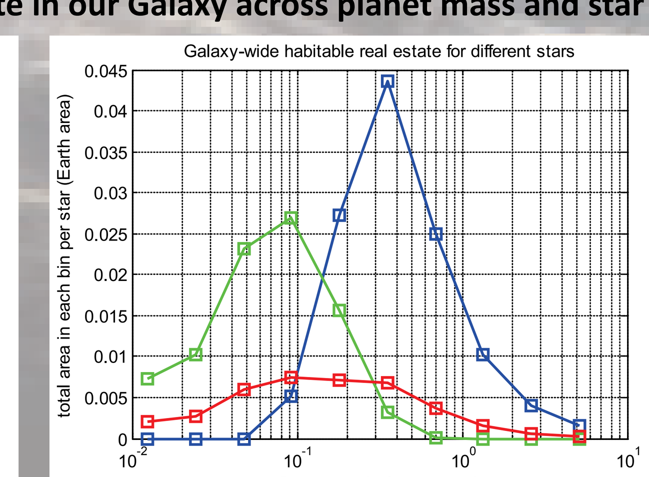
Habitable zones for the Earth analogue branch (blue) and the tidally locked branch (green), along with the maximum distance for tidal locking for different mass planets. Note that:
• The habitable zone for tidally locked planets as we defined it is 4 x wider than the conventional habitable zone
• Larger planets are more likely to be tidally locked



Fraction of the surface of a tidally locked planet that is habitable. Note that as much as 35% of a tidally locked planet's surface may be habitable, and the average amount is about 25%.

Histograms of habitable real estate in our Galaxy across planet mass and star mass





Blue: Earth-analogue branch
Green: tidally locked branch
Red: Jovian moon branch

- There is about 0.25 Earth-area of habitable surface on planets orbiting a star, on average
- It is more likely to be on a smaller planet because they are more numerous
- Around a Sun-like star, eta_Earth (in the habitable zone) is:
  - For planets from 1 to 2 Earth radius: 7%.
  - For planets from 0.5 to 2 Earth radii: 34%
- On the Earth-analogue branch, habitable area is (slightly) more likely to be on small planets
  - Because small planets are intrinsically more numerous
- On the tidally locked branch, habitable area is (sligthly) more likely to be on large planets
  - Because larger planets lock sooner
- Jovian moons are (slightly) more likely to be large
- The most likely habitable star is:
  - Earth analogue branch, and overall: 0.3-0.4 M_{sun}
  - Tidally locked branch: 0.05-0.1 M_{sun}
  - Jovian moon branch: 0.05 – 1 M_{sun} are about equally likely
- Soft boundary between the Earth-analog and tidally locked branches, around 0.1-0.2 solar masses.
- The tidally locked planets and Earth analog have comparable total area. The reduced amount of area on the tidally locked planets is compensated by the increased range of semi-major axis.
- The Jovian moon case is also fairly comparable to the rocky planet cases. Even though the moon area and number is assumed to be very small, the range of Jovian semi-major axes and eccentricities is very large.

Conclusions

- There is about 1 Earth area of habitable surface per 4 stars
- Most of this real estate is contained in Earth analogues, but the contributions by tidally locked planets and Jovian moons are surprisingly comparable
- For the Earth-analogue branch, eta_Earth ranges from 7 to 34%, depending on the lower mas cut-off (1 or 0.5 Earth radii)
- Around stars with 0.1 solar masses and below, most of the real estate is contained in planets that are tidally locked, while around heavier stars most of the real estate is in Earth analogues.
- A key ingredient in our model is the distribution of planet masses based on dynamical considerations as well as observations from Kepler