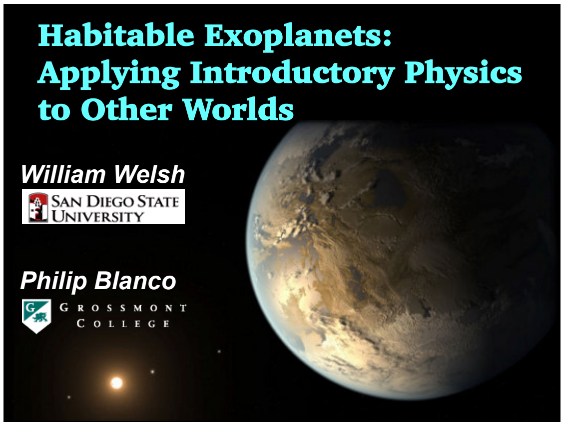
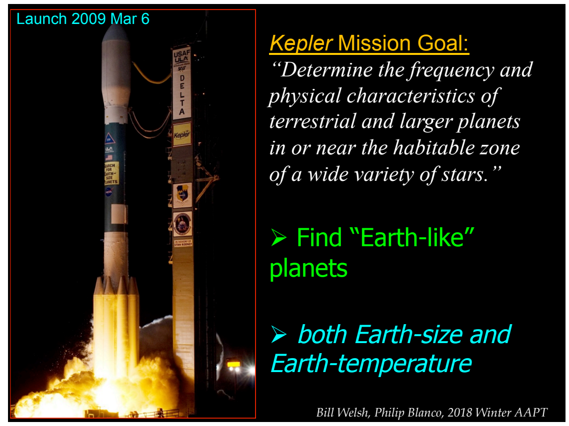
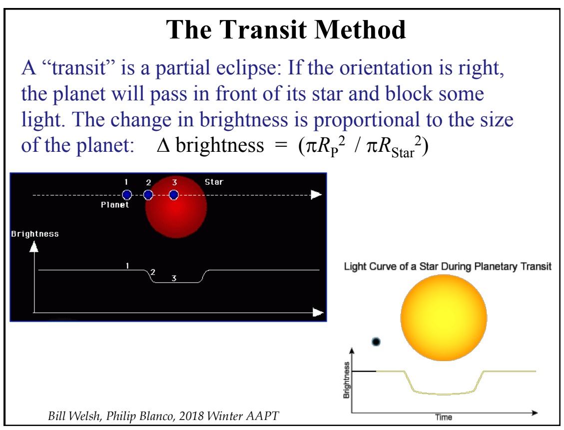
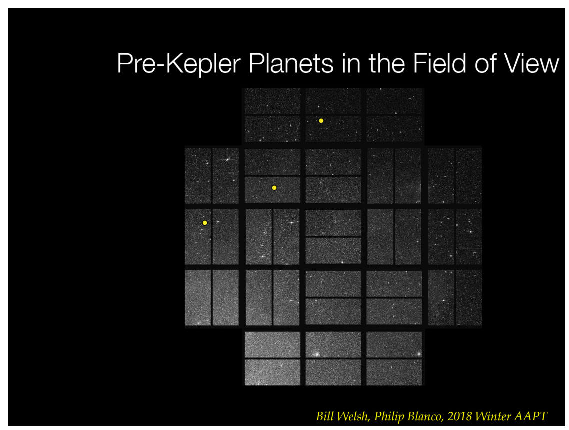
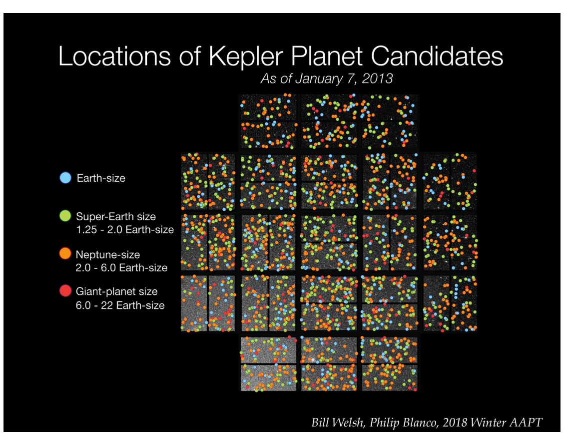
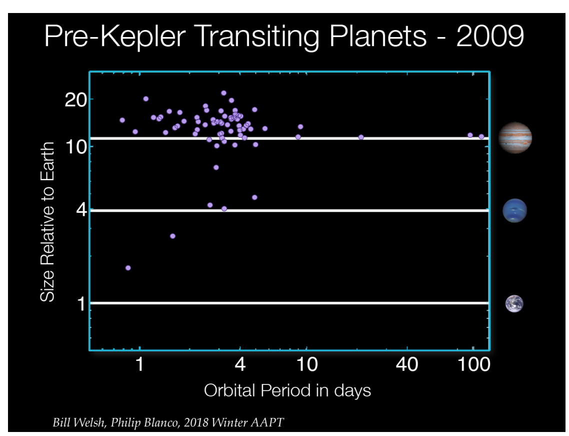

Habitable Exoplanets:
Applying Introductory Physics
to Other Worlds
William Welsh
San Diego State University
Philip Blanco
Grossmont College


Launch 2009 Mar 6
Kepler Mission Goal:
"Determine the frequency and physical characteristics of terrestrial and larger planets in or near the habitable zone of a wide variety of stars."
➢ Find "Earth-like" planets
➢ both Earth-size and Earth-temperature
Bill Welsh, Philip Blanco, 2018 Winter AAPT


The Transit Method
A "transit" is a partial eclipse: If the orientation is right, the planet will pass in front of its star and block some light. The change in brightness is proportional to the size of the planet: Δ brightness = $(\pi R_P^2 / \pi R_{Star}^2)$
Star
Planet
Brightness
Light Curve of a Star During Planetary Transit
Brightness
Time
Bill Welsh, Philip Blanco, 2018 Winter AAPT

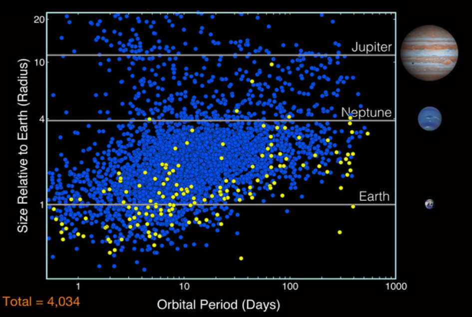

Pre-Kepler Planets in the Field of View
Bill Welsh, Philip Blanco, 2018 Winter AAPT


Locations of Kepler Planet Candidates
As of January 7, 2013
Earth-size
Super-Earth size
1.25 - 2.0 Earth-size
Neptune-size
2.0 - 6.0 Earth-size
Giant-planet size
6.0 - 22 Earth-size
Bill Welsh, Philip Blanco, 2018 Winter AAPT

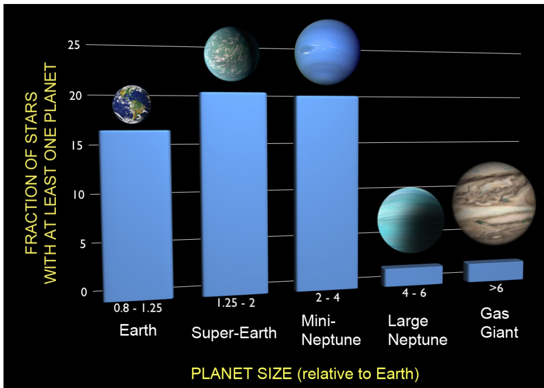

Pre-Kepler Transiting Planets - 2009
Size Relative to Earth
20
10
4
1
1
4
10
40
100
Orbital Period in days
Bill Welsh, Philip Blanco, 2018 Winter AAPT

Kepler Planet Candidates

As of June 2017



Bill Welsh, Philip Blanco, 2018 Winter AAPT



Bill Welsh, Philip Blanco, 2018 Winter AAPT

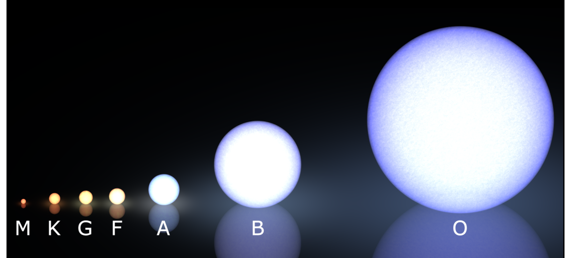
Kepler's main result: Earth-like planets are NOT rare!

- **2341 confirmed planets** (as of 2018 Jan 5)
  plus 2155 additional planet *candidates*
- **Most common planet: "super Earth"**
  R_P **= 1.25 - 2.0** R_{Earth} **– nothing similar in our Solar System!**
- **290 candidate planets in the Habitable Zone (*HZ*)**
  – 22 with radius < 1.25 R_{Earth} **← potentially Earth-like**

Occurrence of Earth-size planets in the *HZ* is:
~ 22% for sun-like stars (G, K type)
~ 50% for small faint stars (M type)

Bill Welsh, Philip Blanco, 2018 Winter AAPT

Star sizes and colors shown to scale, by spectral type

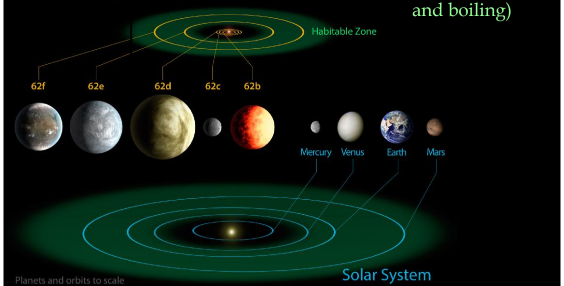


Bill Welsh, Philip Blanco, 2018 Winter AAPT

The Habitable Zone (*HZ*)

Distances from a star such that a rocky planet could have liquid water on its surface (temperature between ~ freezing and boiling)

Kepler-62 System



Bill Welsh, Philip Blanco, 2018 Winter AAPT

Thermal Energy balance for planet

Energy out = Energy in.

$$L_P = \frac{L_{star}}{4\pi\, d^2}\left(\pi R_P^2\right)(1-A)$$

A is the *Bond Albedo* (reflectivity)
A=0 blackbody
A=1 shiny ball

Now assume:
- Stefan-Boltzmann law (blackbody) for planet and star
- atmosphere distributes energy over entire planet surface

$$\left(4\pi R_P^2\right)\sigma T_{eq}^4 = \frac{\left(4\pi R_{star}^2\right)\sigma T_{star}^4}{4\pi d^2}\left(\pi R_P^2\right)(1-A)$$

$$\Rightarrow T_{eq} = T_{star}\left(\frac{R_{star}}{2d}\right)^{1/2}(1-A)^{1/4}$$

Albedo $A \approx$ 0.3 for solar system and a few exoplanets; our guess does not have to be accurate!

So we know all the parameters: T_{star}, R_{star}, d, **and** A.

Bill Welsh, Philip Blanco, 2018 Winter AAPT

Thermal Energy balance: Disclaimers!

$$T_{eq} = T_{Star}\left(\frac{R_{Star}}{2d}\right)^{1/2}(1-A)^{1/4}$$

NOTE: *HZ* and T_{eq} are starting points - DO NOT imply life, or even the conditions for life!

T_{eq} ignores other sources of heating: tidal, radioactivity, gravitational compression, greenhouse effect; e.g.

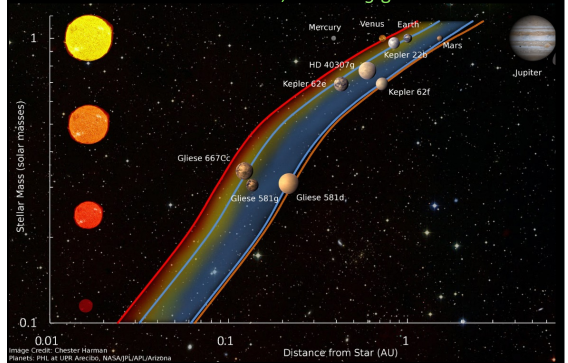
- T_{eq} for the Earth is -18° C instead of 15° C!
- Jovian icy moons are not in the HZ; the Earth's Moon is!

We also don't know the composition of the planet's atmosphere (yet), so we cannot compute the actual temperature.

But the *HZ* and T_{eq} concepts help us decide which of the thousands of exoplanets to focus on.

Bill Welsh, Philip Blanco, 2018 Winter AAPT

Habitable zones around stars, *including* greenhouse effect



Bill Welsh, Philip Blanco, 2018 Winter AAPT

Student explorations: How "Earth-like" is an exoplanet?

What *Kepler* results and stellar astrophysics tell us:

- planet's radius R_P
- distance *d* from star, star properties (luminosity/temperature/radius/lifetime)

➔ T_{eq}, position in habitable zone plot

Additional info needed to compare with Earth conditions:

$$\text{Surface gravity : } g = \frac{GM_P}{R_P^2}$$

$$\text{Escape speed } v_{esc} = \sqrt{\frac{2GM_P}{R_P}}$$

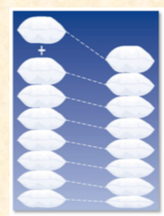
- Useful to guess what *kind* of atmosphere the planet can hold, and surface state of H_2O, CH_4, NH_3, etc.
- **But BOTH require an estimate of planet's MASS M_P ...**

Bill Welsh, Philip Blanco, 2018 Winter AAPT

To estimate exoplanet's mass, need to measure a gravitational interaction…

- **Doppler reflex motion of the star**
  - radial velocity from spectroscopy
- **planet-planet interactions**
  - transit timing variations (deviations from strict periodicity)

OR…



- *Choose* a model composition / equation of state (mass vs. radius)
- due to core compression, the density will not be constant for a given composition, i.e.

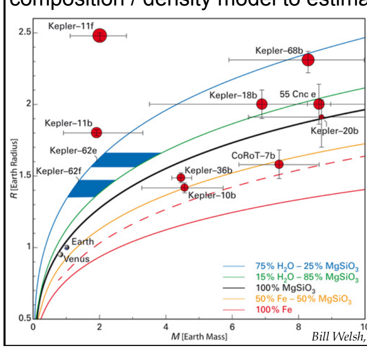
$$M_P \text{ is not } \propto R_P^3, \text{ more like approx. } \propto R_P^2$$

$$\Rightarrow \rho_{av} = \frac{M_P}{\frac{4}{3}\pi R_P^3} \text{ approx.} \propto \frac{1}{R}$$

Bill Welsh, Philip Blanco, 2018 Winter AAPT

Density models: Estimating Mass given Radius

Given R_P from *Kepler* data, need to choose a composition / density model to estimate Mass M_P

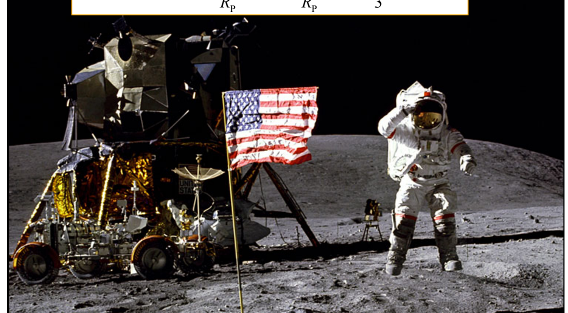


$$\rho_{av} \equiv \frac{M_P}{\frac{4}{3}\pi R_P^3} = 5514\,\text{kg/m}^3\,\frac{\dfrac{M_P}{M_{Earth}}}{\left(\dfrac{R_P}{R_{Earth}}\right)^3}$$

Fressin et al. (2012) *Nature*

Bill Welsh, Philip Blanco, 2018 Winter AAPT

$$\text{Surface gravity } g = \frac{GM_P}{R_P^2} = \frac{G\left(\rho_{av}\frac{4}{3}\pi R_P^3\right)}{R_P^2} = \frac{4}{3}\pi G\left(\rho_{av}R_P\right)$$



How much do you weigh? How high can you jump?
$g \neq 9.8\ \text{m/s}^2$ for many bodies in the universe!

Hold on tight - to your atmosphere!

Kinetic gas theory: $v_{rms} = \sqrt{\frac{3k_B T_{\text{Gas}}}{m\ (\text{kg})}} = 157\text{m/s}\sqrt{\frac{T_{\text{Gas}}}{m\ (\text{amu})}}$

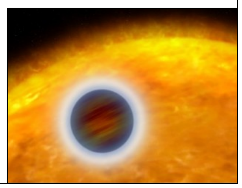
For $T_p \approx 300\text{K}$ (in habitable zone):

$v_{\text{RMS}}(\text{He}) \approx 1400\ \text{m/s}, \quad v_{\text{RMS}}(H_2O\ /\ CH_4\ /\ NH_3) \approx 680\ \text{m/s}.$

Should have atmosphere's $v_{\text{RMS}} \ll v_{\text{esc}} = \sqrt{2GM/R} = \sqrt{2gR} = \sqrt{\frac{8\pi G}{3}}\sqrt{\rho_{av}}R$

Unknown: atmospheric *pressure*! Determines surface state of water, methane, ammonia.

"Gas giants" in HZ are okay – may have habitable moons!



Bill Welsh, Philip Blanco, 2018 Winter AAPT

Escape speed, thermal speed – what kind of (possible) atmosphere?

***Escape*:**

$$v_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{2gR} = \sqrt{\frac{8\pi G}{3}}R\sqrt{\rho_{av}}$$

$$= 11\ \text{km/s}\frac{R}{R_{Earth}}\sqrt{\frac{\rho_{av}}{\rho_{Earth}}}$$

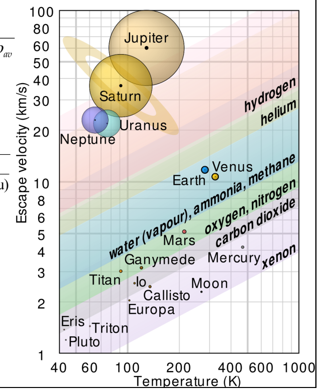
***Thermal*:**

$$v_{\text{RMS}} = \sqrt{\frac{3k_B T_{\text{Gas}}}{m\ (\text{kg})}} = 0.157\text{km/s}\sqrt{\frac{T_{\text{Gas}}}{m\ (\text{amu})}}$$

BUT…

- T_{Gas} may not be the same as T_{eq}
- Nonthermal mechanisms also cause atmospheric escape
- Atmospheric *pressure* unknown!

***SO (for now!)*:**
Take a cue from our solar system objects with atmospheres:



Student Investigations Summary

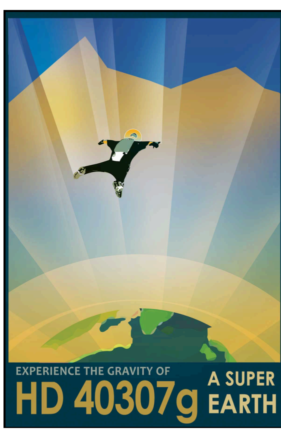
1. Pick an exoplanet (database) by transit *Period.*
2. Research *star's* properties: M_{Star}, T_{Star}, R_{Star}
3. Transit depth → R_{P}. Period → d (Kepler's 3rd law)
4. Calculate $T_{\text{eq.}}$ Also plot planet's position on HZ graphs
5. Use R_{P} vs. M_{P} models to estimate a range for M_{P}
6. Calculate plausible ranges of g, v_{esc}
7. Calculate v_{RMS}, investigate possible atmospheres.
8. ***Enjoy your new destination!***

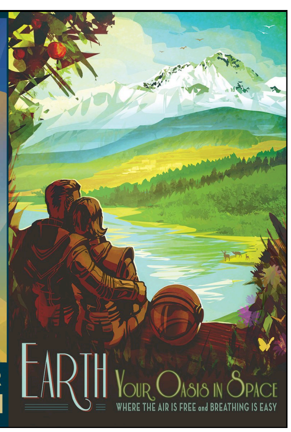
Bill Welsh, Philip Blanco, 2018 Winter AAPT

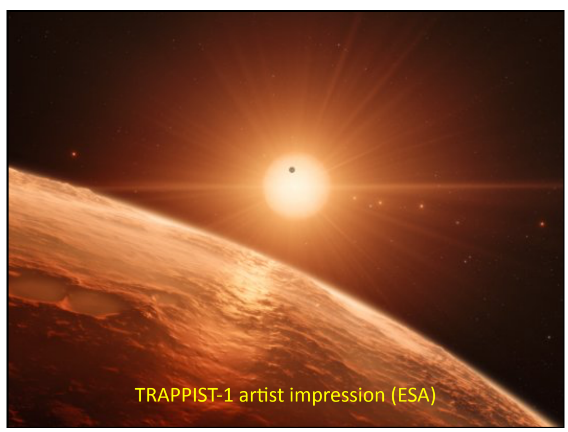
Resources for Student Investigations

- **Pick an exoplanet for analysis:** www.openexoplanetcatalogue.com
- **New Worlds Atlas:** https://exoplanets.nasa.gov/newworldsatlas/
- **Habitable Zone gallery:** http://www.hzgallery.org/
- **NASA Exoplanet Archive** (latest tally, downloadable tables, plots):
  - http://exoplanetarchive.ipac.caltech.edu
- Build your own exoplanet and other activities:
  - **NASA/JPL PlanetQuest**: http://planetquest.jpl.nasa.gov/
- **Exoplanet App** for your smart phone: http://exoplanetapp.com/
- **Planet Hunters** (a citizen science project): https://www.planethunters.org/

Bill Welsh, Philip Blanco, 2018 Winter AAPT







TRAPPIST-1 artist impression (ESA)