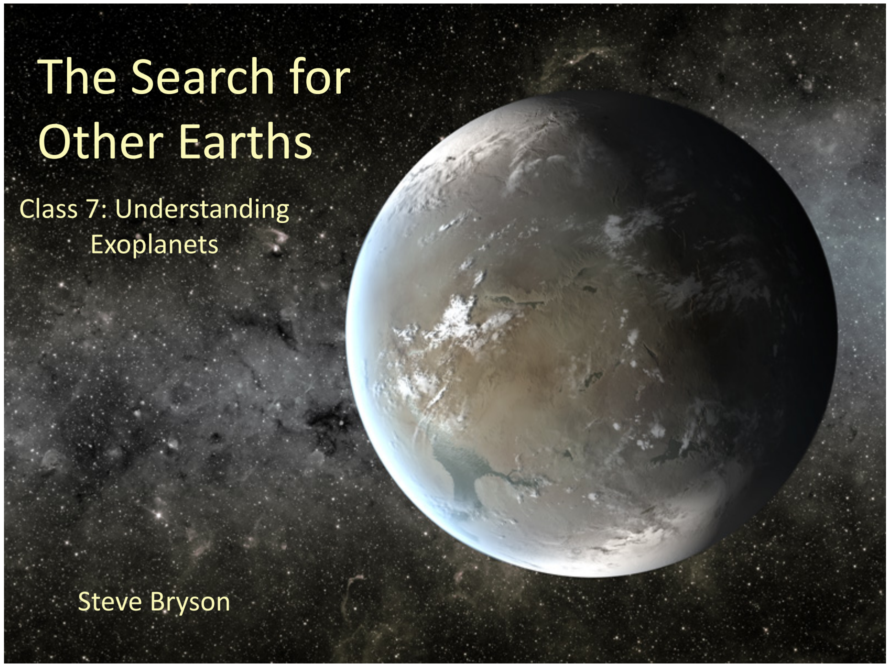
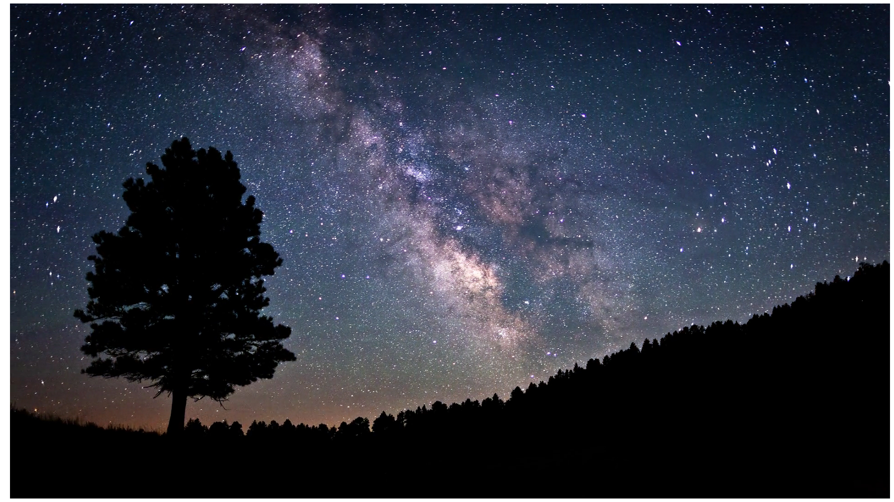
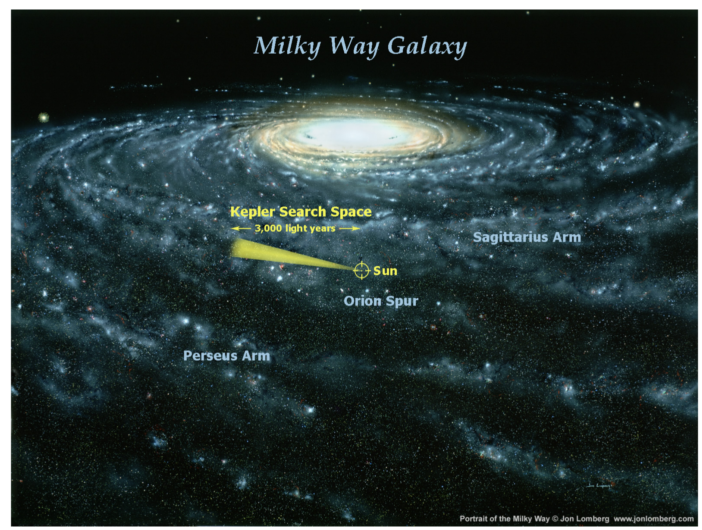


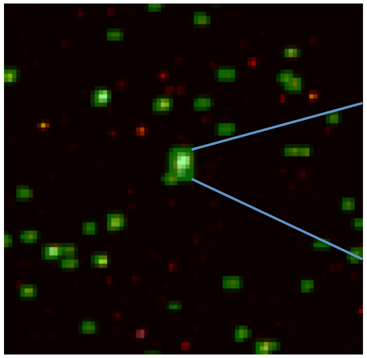
Questions?



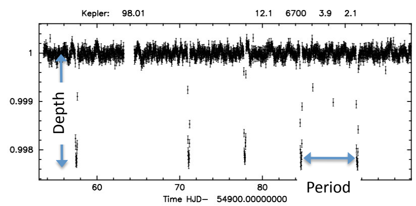
Kepler Searches a Small but Significant Part of the Galaxy



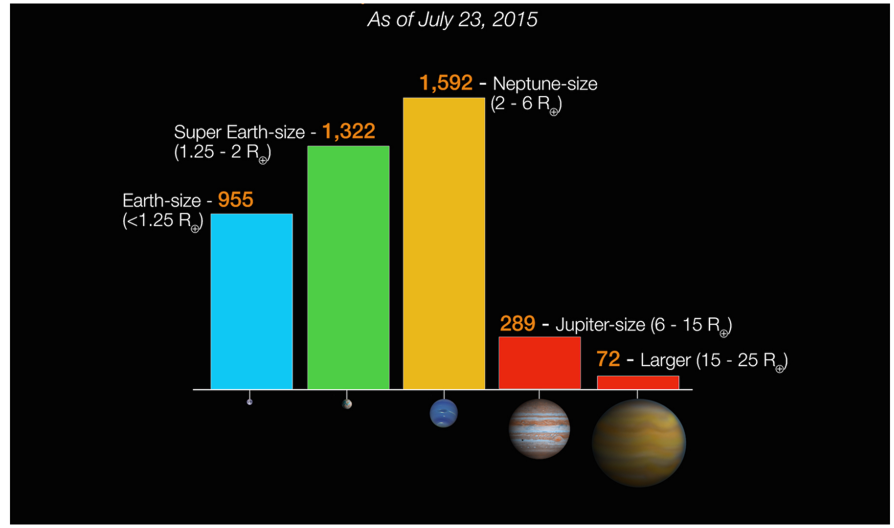
Transits Measure Planet Radius and Orbital Period



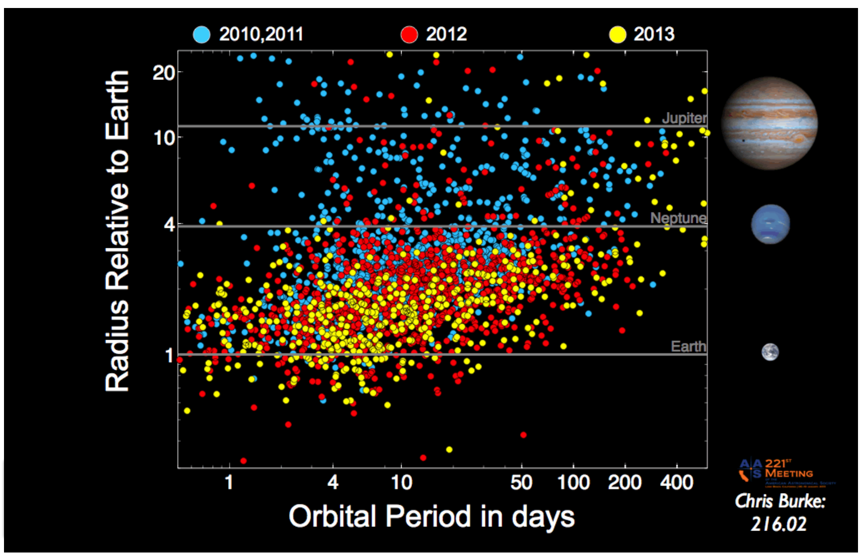
- The Depth tells you the fraction of the star covered by the planet
  - Tells you the size of the planet
- The time between transits is the period of one orbit of the planet around its star



Kepler Candidate Planet Sizes

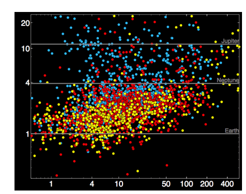


Kepler Planet Size and Orbital Period

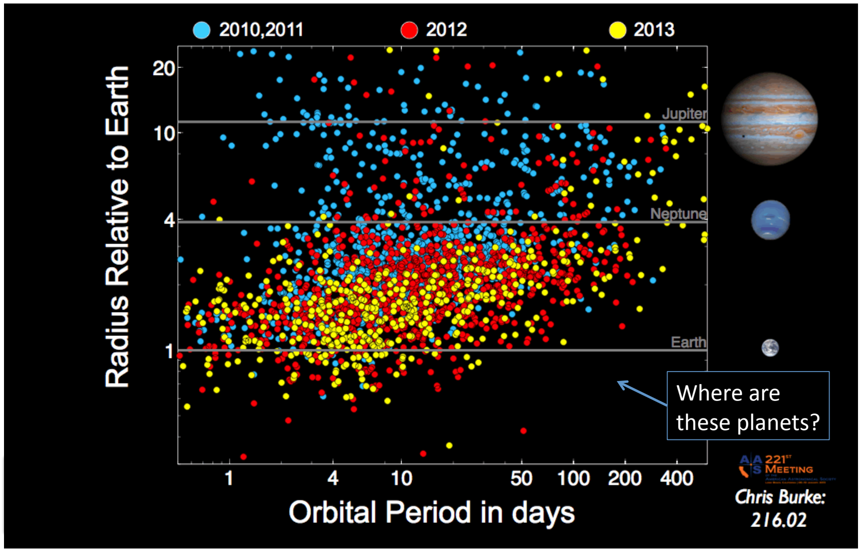


How Many Planets of Each Type

- Big question: how many planets are there broken down by size and orbit period
  - Size tells us planet type
  - Orbit tells us planet temperature
    - Both explained later in this class
- We know how many planets of each type were found by Kepler
- But how many were missed?

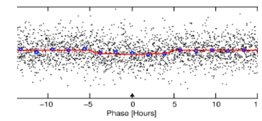


Kepler Planet Size and Orbital Period



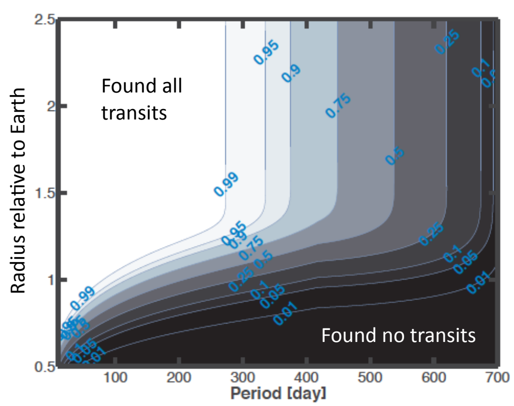
Some Transits are Very Hard to Find

- Small planets in long-period orbits have only 3 or 4 small-transit signals
- Most of these will be missed
- Measure the miss rate
  - Depends on planet size and orbit period
  - Simulate transits of each planet type on all the stars, see how many of the simulated transits are found
    - Paper by Jessie Christiansen et. al. released last night!
- Correct the measured number of planets of each type to estimate the true number



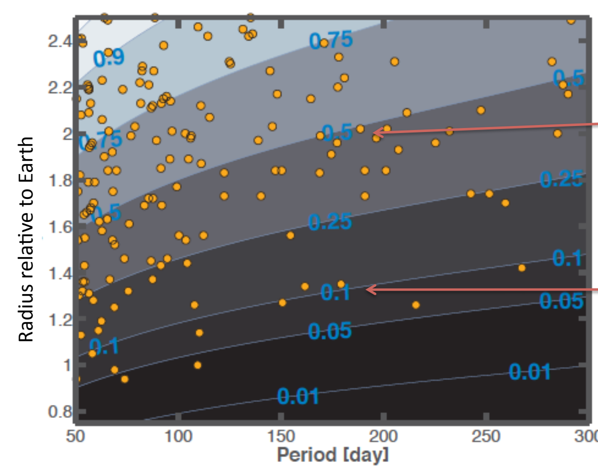
Completeness Contours

- *Completeness contours* give the result of the miss rate measurement



Correcting the Planet Number

Closeup of completeness contours with planets found by 2015



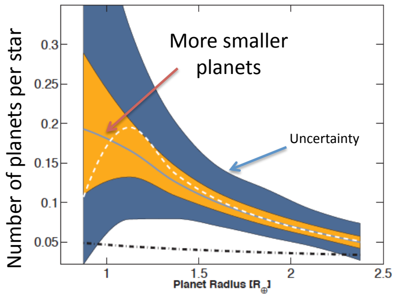
Probably actually twice as many here

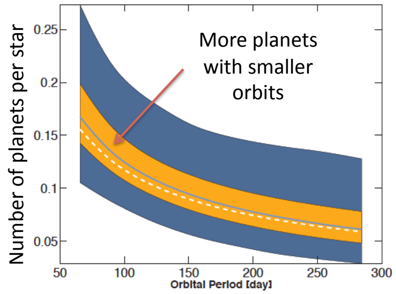
Probably actually 10 times as many here

(assuming none of these detected transits are false alarms)

How Many Planets per Star?

- For planets between 0.75 and 2.5 times the size of the Earth with orbits between 50 and 300 days: 0.77 planets/star
  – Chris Burke et. al. 2015



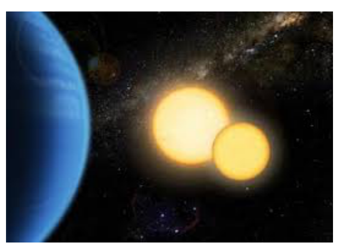


OK, But What About Earth Analogs?

- How many Earth-size planets in 1-year orbits around Sun-like stars?
  – Within 20%
  – Essentially no clear transit detections
    - The few we have may all be false alarms
  – So this is a very difficult measurement
- People try anyway, get a wide range of answers:
  – Youdin et. al. 2011: 0.5 (1 every 2 stars)
  – Petigura et. al. 2013: 0.02 (1 every 50 stars)
  – Dong and Zhu 2013: 0.03 (1 every 31 stars)
  – Foreman-Mackey et. al. 2014: 0.004 (1 every 225 stars)
  – Burke et. al. 2015: 0.1 (1 every 10 stars)
  – Traub 2016: 0.15 (1 every 6 stars)
- Different methods and different assumptions
  – We're still working on it…

What About Multiple Stars?

- Planets have been found around binary stars
  – Proving planets can form in binary star systems
  – Sometimes large orbit around both stars, sometimes orbiting individual stars in the system
- About half the stars in the sky are binary (or more) stars
- A new (last month) study suggests that there are fewer planets around binary stars
  – About a third as around single stars

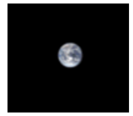


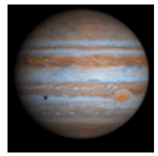
What are These Planets Actually Like?

- What can we say about a planet if we know
  – Its size?
  – Its orbit?
  – Its star?

From Planet Size We Infer Type

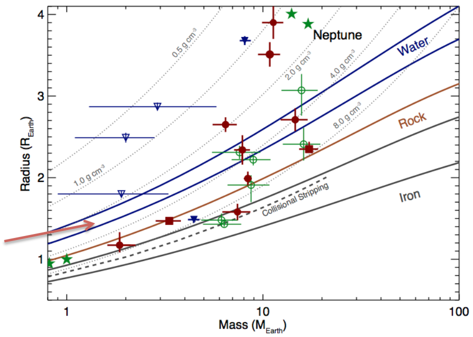
- Small planets mostly rock or iron
- In between planets mostly water, methane, …
- Big planets are mostly Hydrogen and Helium gas





Dots are planets where we've measured both size and mass

Lines assuming made of nothing but iron, rock or water



From Planet Size We Infer Type

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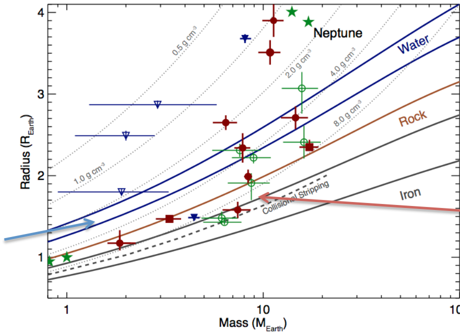
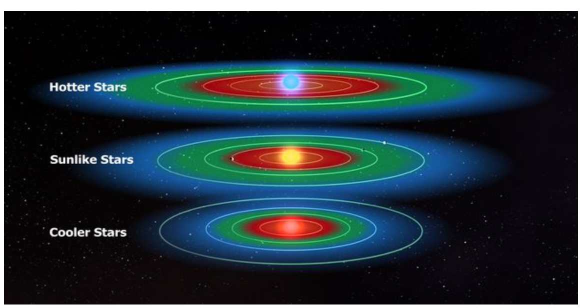


See how the planets follow the rock line until here?

A careful study by Leslie Rogers (2014) says that planets larger than 1.5 time Earth are probably not rocky

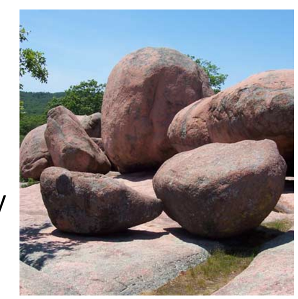
From the Orbit We Infer Temperature

- To estimate a planet's temperature, we need to know how much light is falling on the planet
  - Brightness and distance of the star

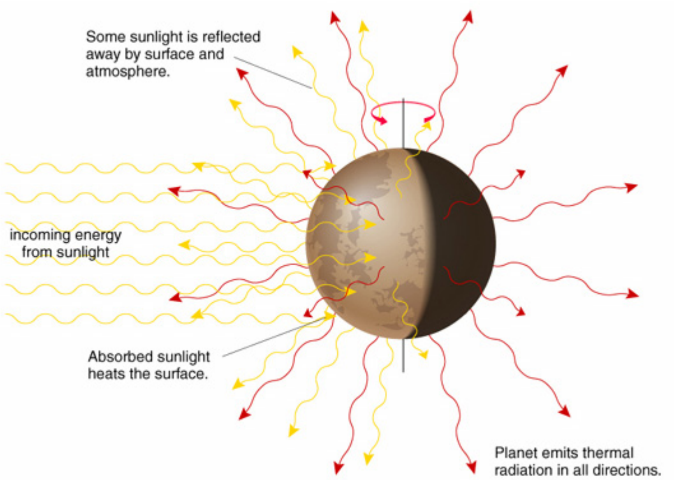


How Hot is a Planet?

- How Hot is a rock?
- Why does a rock in sunlight get as warm as it does?
  - Energy from the Sun is absorbed, heating the rock
  - Energy from the rock is radiated away as warmth (heat)
  - The rock stops warming up when the amount of energy radiated away as heat is equal to the amount absorbed from the sunlight
- Planets work the same way!

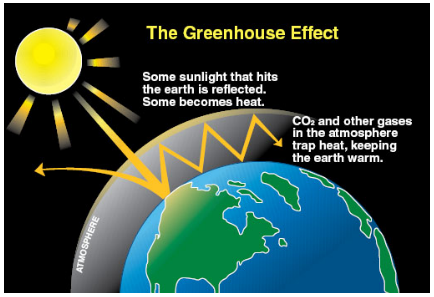


Planet Temperature is Determined by Energy Balance



Atmosphere is Important

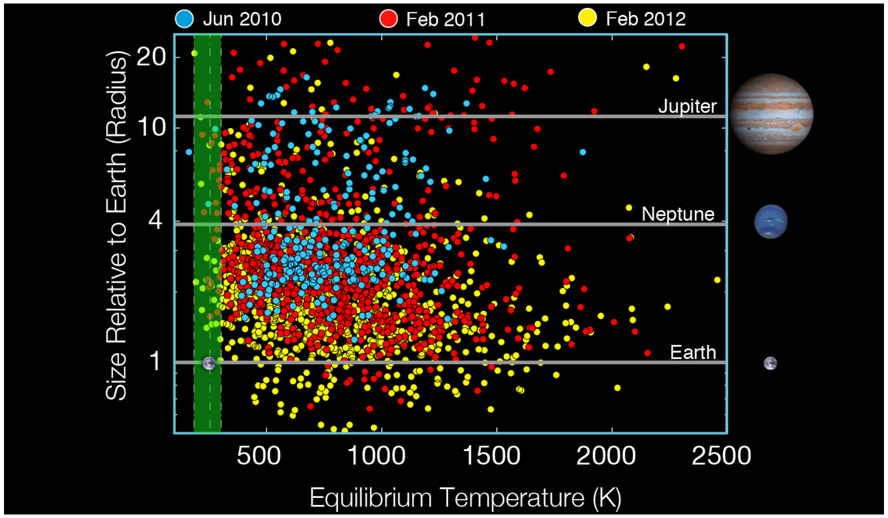
- The more light from the star, the hotter the planet is before there is energy balance
- The atmosphere of the planet matters
  - Greenhouse gases trap the heat, so the planet has to be hotter to reach balance



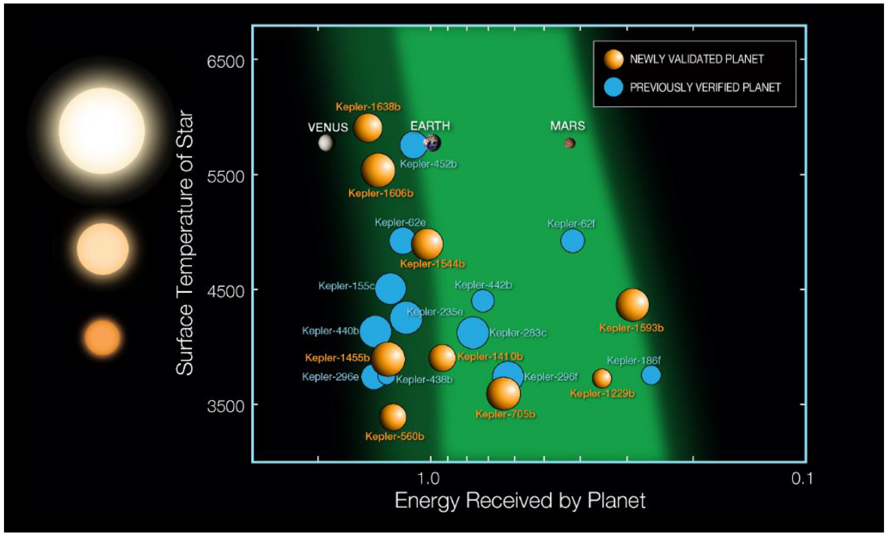
So Where is the Habitable Zone (HZ)?

- Where the planet reaches an energy balance at a temperature that allows liquid water
- HZ will be further from the star if the planet has a heat-trapping atmosphere
  - So if we don't know the atmosphere we are a little uncertain about the atmosphere
  - "Conservative HZ": where most atmospheres are OK
  - "Liberal HZ": where the atmosphere has to be just right

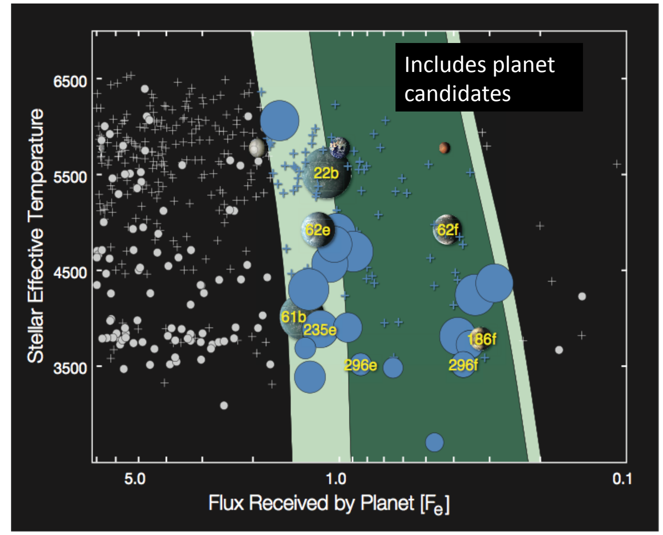
Planet Size and Temperature



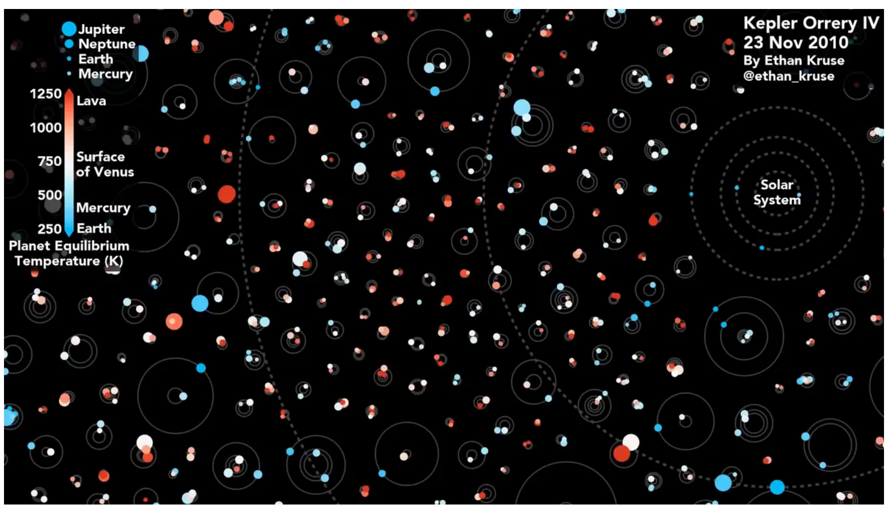
What About the Habitable Zone?



What About the Habitable Zone?

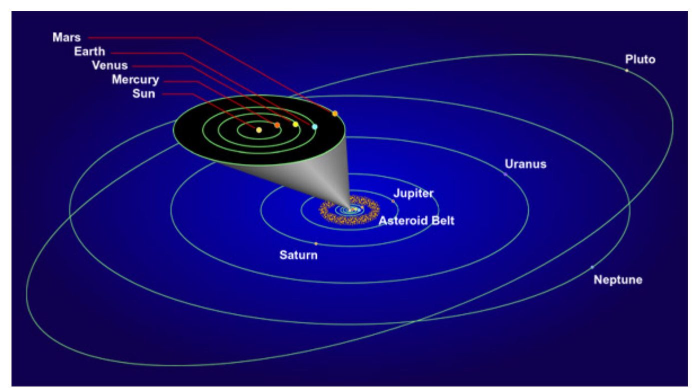


719 Multiple Planet Systems!



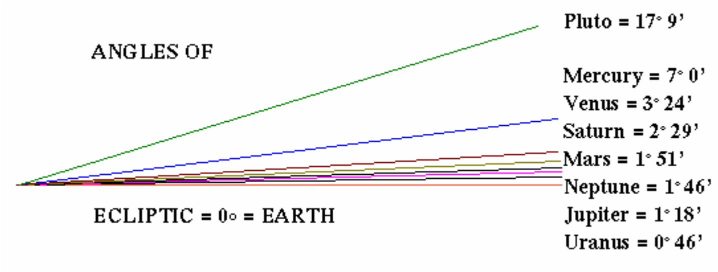
Why Do We See So Many Multiple Planet Systems?

- The planets in our Solar System are almost orbiting in the same plane



Why Do We See So Many Multiple Planet Systems?

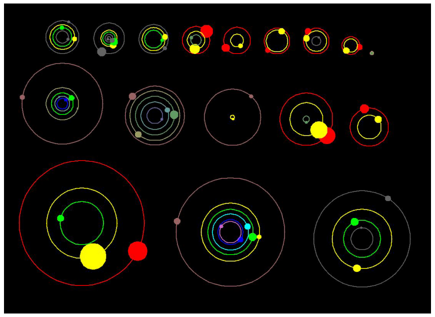
- But only almost in the same plane



- So if one of our planets transits when seen from another star, the others probably do not

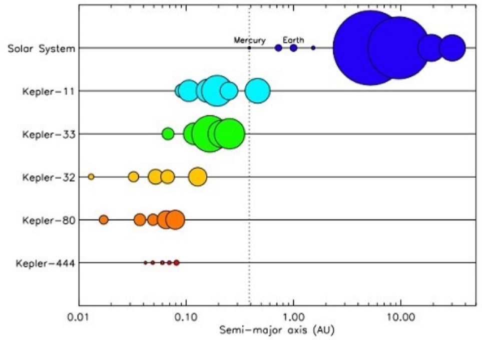
So the Kepler Systems Must Be Flat

- When we see several planets transiting, the system must be flatter than our Solar System
  - It is a challenge to explain this with current planet creation theories



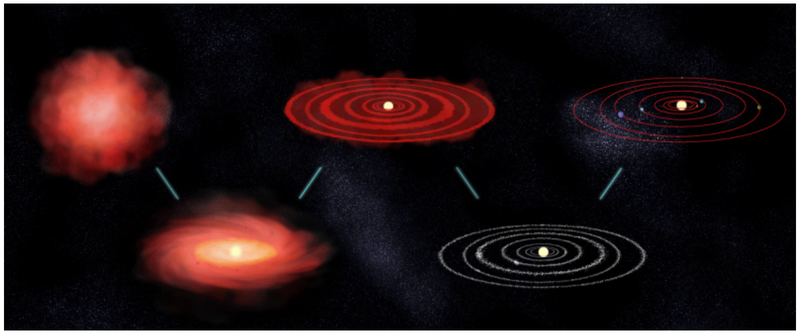
Kepler Systems are Very Densely Packed

- The planet orbits are much closer together than in our Solar System
  - Often on the edge of instability: if the planets were closer together their mutual gravity would disrupt the system



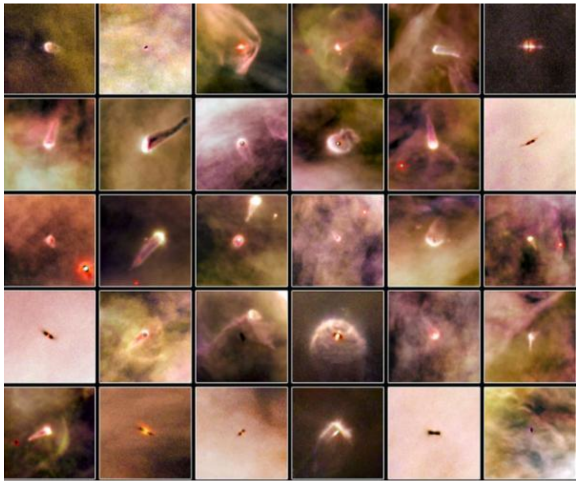
Creation of Planetary Systems

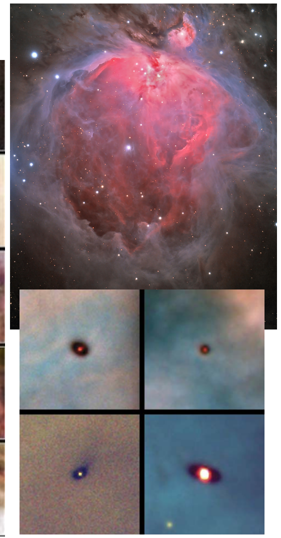
- We believe that the Solar System formed at the same time as the Sun from the same cloud of gas



Pictures of Forming Stars and Planets

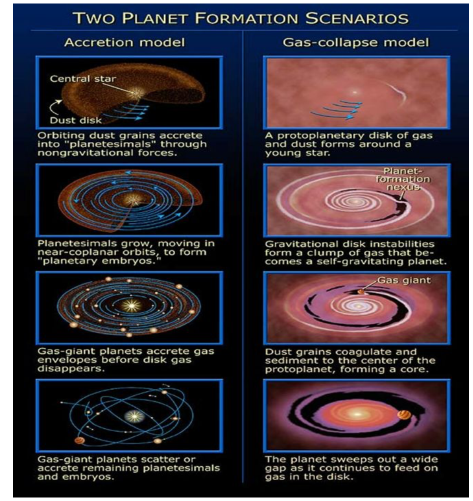
In the Orion Nebula





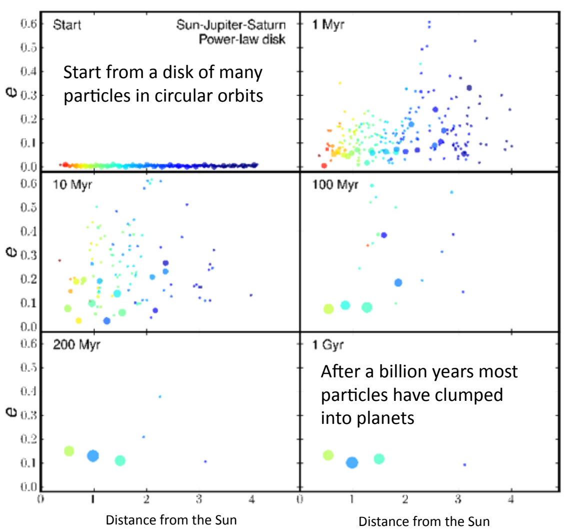
Planets form by Collapsing Gas and Collisions (Accretion)

- Collapsing gas forms the gas giants
  - Quickly: < 1 million years
- Accretion forms the small planets
  - More slowly: 3 to 10 million years

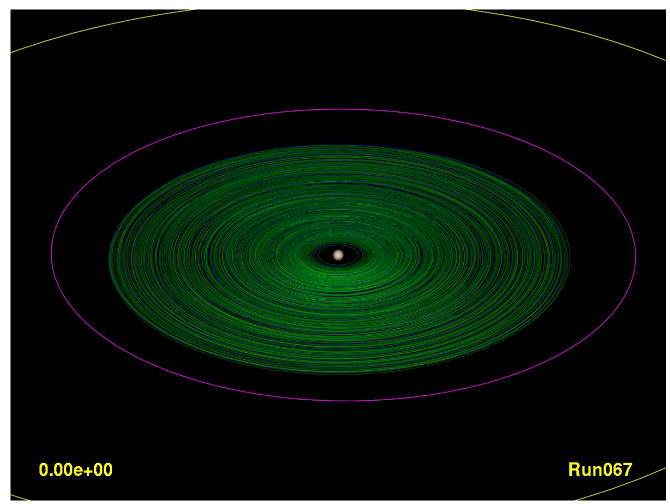


Simulation of the Inner Solar System

- Forming by accretion, starting from a disk of very small particles
- The vertical axis shows how elliptical the orbit is



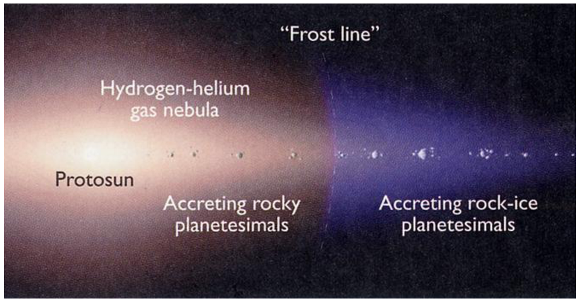
Simulation of the Inner Solar System



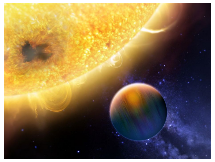
Simulations by Elisa Quintana

Distance from the Young Sun Matters

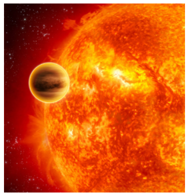
- Closer to the young Sun the gas is too hot to collapse
- Further from the Sun some gases can freeze, creating the seeds of the giant planets
- The division between these is called the *snow line*
  - Gas giant planets form outside the snow line
- Between 2.5 and 3 AU for the Solar System



Jupiters in the Wrong Place

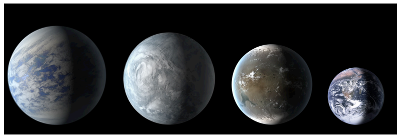


- Jupiters can form only outside the snow line
- Hot Jupiters close to their star must have migrated after forming
  - Migrated by interacting with other planets
    - Often ejecting the smaller planets from the system
  - Hot Jupiters are lonely
    - Rarely in multiple systems in Kepler data
    - Supports the theory of migration

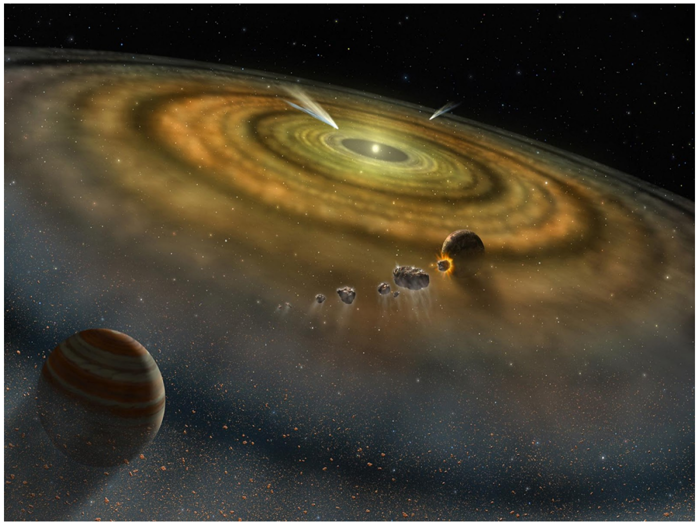


What About Life?

- Currently we can't detect life on exoplanets
- We know a lot about how biology works
- But not much about how biology got started
- So we don't know what is required for life
  - Stick to what we know
    - But don't ignore other possibilities
- Perhaps Super Earths are good for life
  - More active geology provides more good minerals

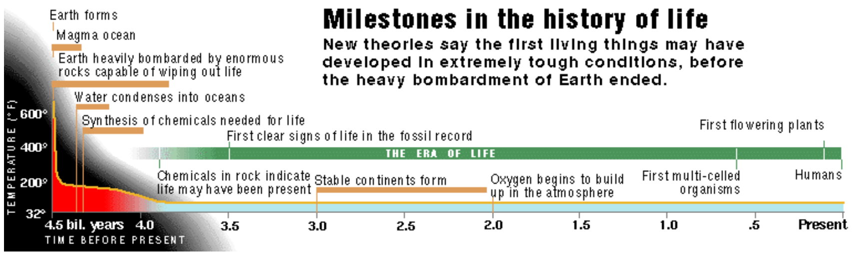


The Infant Solar System was a Very Unfriendly Place



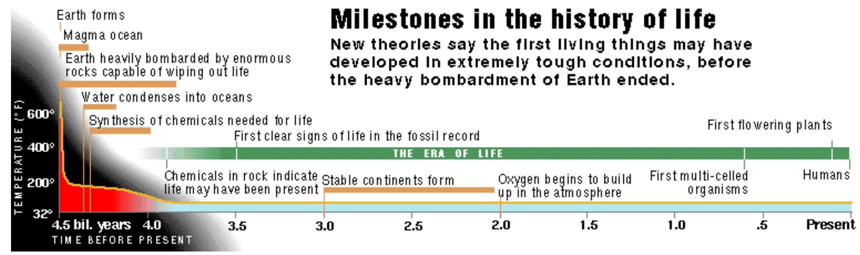
Life on Earth Happened Quickly

- We have evidence for simple life almost as soon as Earth was cool enough to allow it
  - Does this mean that the creation of life is probable?



But Complex Life Took a Long Time

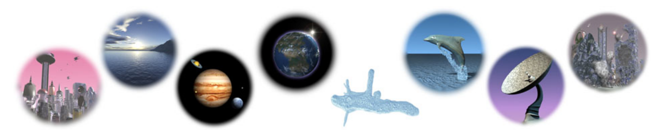
- Multi-celled animals took a lot longer
  - Does this mean that the evolution of complex life is less probable?



What About Other Civilizations?

- Depends on
  - How many stars
  - What fraction of those stars have planets
  - What fraction of those planets are Earth-size
  - What fraction of those planets have life
  - What fraction of that life evolves intelligence
  - What fraction develop the ability to communicate
  - How long such civilizations live
- Multiply all these together and get the *Drake Equation*

The Drake Equation



$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

- 30 years ago we only knew how many stars there are (R_*)

The Drake Equation

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

- Now we know what fraction of stars have planets (all) and the fraction of planets that are Earth-size (~15%)
- We have to dig more deeply in the data to measure how many Earth-like planets are in the habitable zone