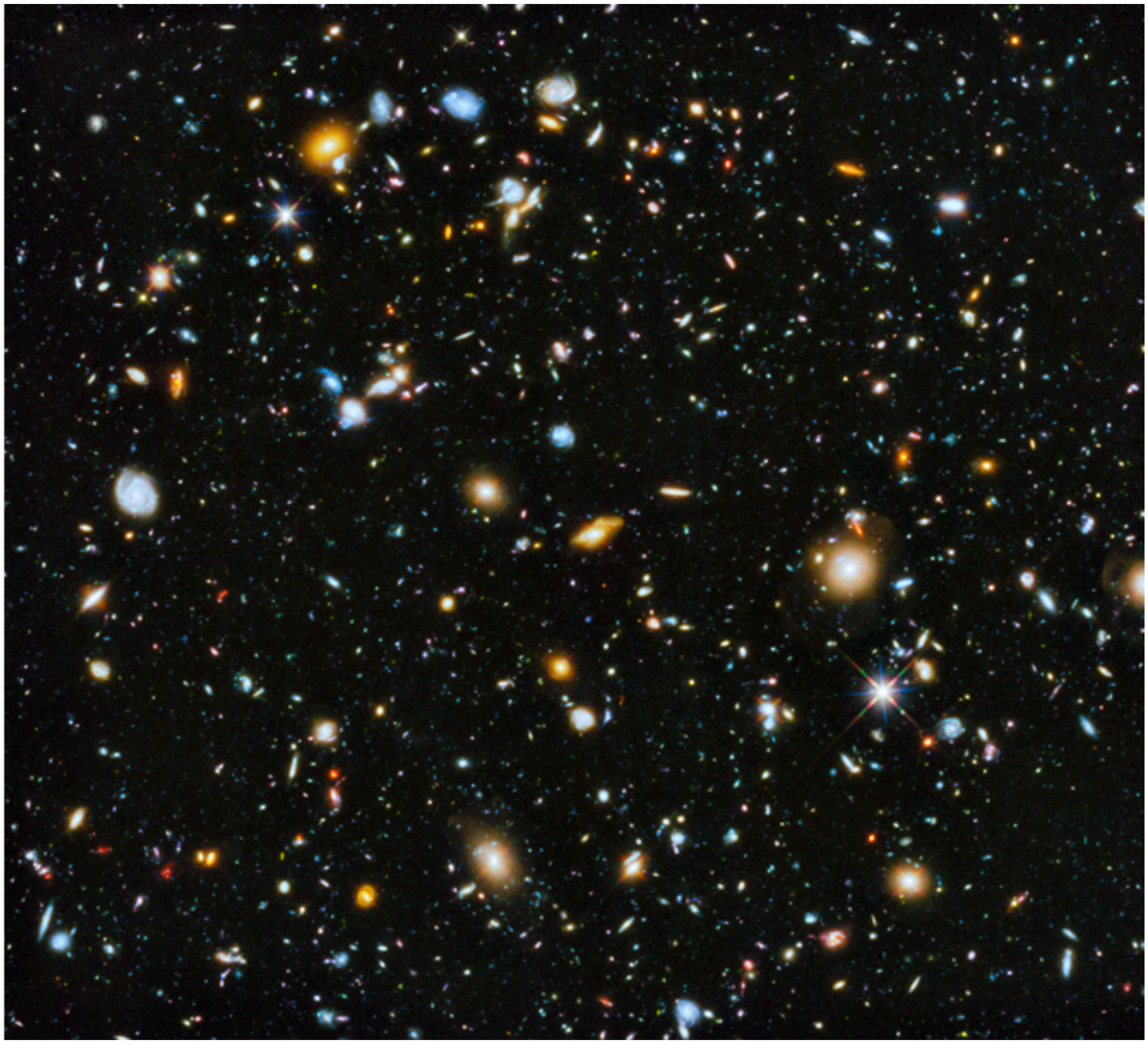
Factor 1: Number of Stars in the Universe



The Hubble Ultra Deep Field is the deepest look we've ever taken into the universe. It showed 10,000 galaxies in one tiny slice of the sky. You would need 13 million Hubble Ultra Deep Fields to cover the whole sky.

There are on average about 100 billion stars in a spiral galaxy, about 10 billion stars in an elliptical galaxy and about 1 billion stars in an irregular galaxy. Galaxies in the universe are 20% spiral, 60% elliptical and 20% irregular.

Use the information in the two paragraphs above to estimate the number of stars in the universe. Show your work below and make sure your answer has a unit.

Factor 2: Average Stellar Lifetime

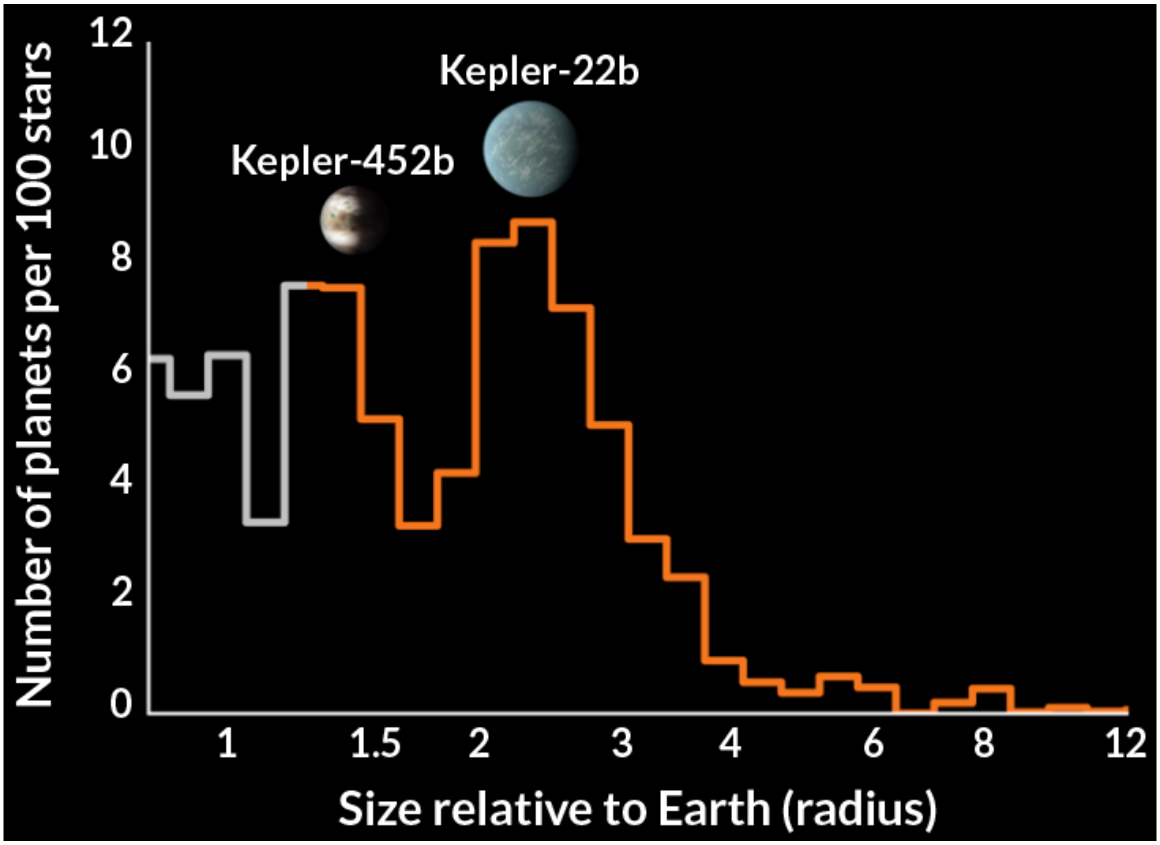
Not all of the stars in the universe are created equally! We give stars "Spectral Classifications", which follow the pattern OBAFGKM from most massive to least, hottest to coolest, largest to smallest and rarest to most common. A good way to remember this is to use the pneumonic "Oh Be A Fine Guy/Girl, Kiss Me", or you can come up with your own (tell a counselor if you come up with a good one!).

The table below lists the average mass (in solar masses, or multiples of the mass of our sun), temperature (in degrees Kelvin), something I've called "Relative Proportion", which you should interpret as answering the question, "for every O star that the universe creates, how many B, A, F, G, K and M stars does it create?", and lifetime (in millions or years). For your reference our sun is a G2 star, slightly hotter (6,000K) and more massive (1 solar mass) than the "average" G star.

Spectral Type	Average Mass (solar masses)	Temperature (Degrees Kelvin)	Relative Proportion	Lifetime (million years)
O	40	38,000	1	3
B	6.5	16,400	72	15
A	2.1	8,620	1,018	500
F	1.29	6,540	3,199	3000
G	0.93	5,610	6,901	10,000
K	0.69	4,640	13,917	15,000
M	0.21	3120	227,838	200,000

Use the table above to estimate the <u>average</u> lifetime of a star in the universe. You will need to use the information in both of the last two columns to compute this. Show your work below and make sure your answer has a unit.

Factor 3: Fraction of Stars with Planets

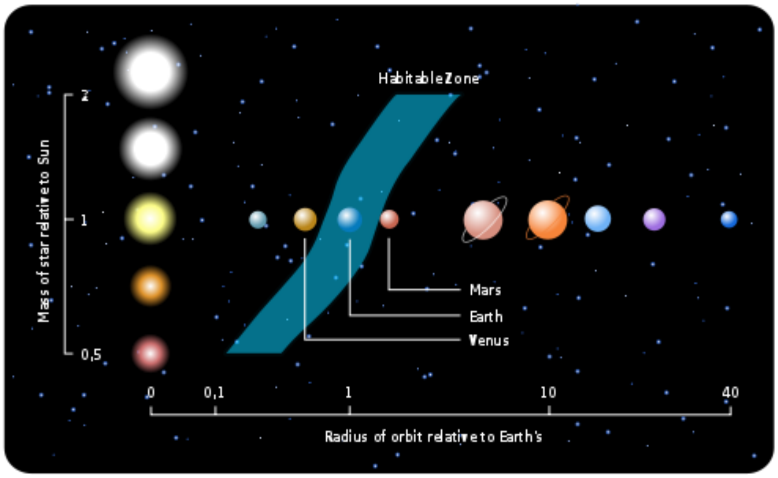


The plot above shows statistics from the NASA Kepler mission's final exoplanet catalog. Use it to estimate how many total planets exist per star. Show your work below and make sure your answer has a unit.

Followup Question:

Given what you know about the transit method and the Kepler mission, are there any planets that might be missing from this data?

Factor 4: Fraction of Planets that Could Potentially Support Life



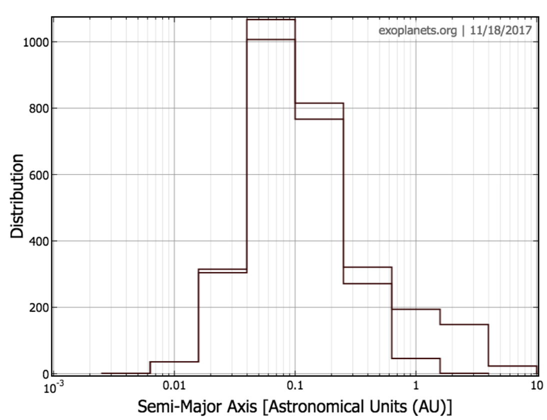
The figure above shows the "Habitable Zone" of different types of stars in blue. The HZ is defined as "the region around a star where temperatures are sufficient for the existence of liquid water". Our solar system is shown next to the G star for your reference.

In terms of how many planets around other stars might be habitable, here again, our best estimates come from Kepler. Kepler found a relatively small number of rocky planets in their stars' HZs, but recall that because the geometric probability of a planet transiting drops off rapidly with distance, this doesn't mean that there aren't unseen (non-transiting) HZ exoplanets around other Kepler stars. Use the statistic below and the charts below and above to estimate the fraction of planets that are habitable.

Hints:

1. *Most of the stars that Kepler studied were "sun-like" F, G and K stars, so use the plot above to estimate the range of distances for the HZ*
2. *Use the chart below to estimate Kepler's relative "completeness" in the region you arrived at through Hint 1. Assume that the universe makes equal numbers of planets around these stars all the way from 0.05AU (the peak of the distribution in the plot below) out to several AU.*

Kepler Statistic - Kepler confirmed exoplanets with $R_p < 2R_{Earth}$ in habitable zone: 30



Given the information above, estimate the factor f_l. Show/explain your work below and make sure your answer has a unit.

Followup Questions:

Looking at the HZ plot, which planets in our solar system (or their moons) would potentially be habitable if we lived around a lower mass or higher mass star?

Why might only $R_p<2R_{Earth}$ planets be considered habitable, when "Super Earths" can have radii up to ~$3.5R_{Earth}$?

Can you imagine habitable worlds outside of the habitable zone? What might make other worlds habitable? Are there examples of potentially habitable worlds outside the HZ in our own solar system? In other words, what are the limitations of the HZ definition?

Given your answer to the questions above, is this estimate for the number of habitable worlds likely an over or under-estimate, and why?

Factor 5: Fraction of Planets that Could Develop Intelligent Life

In this case, the best evidence for this fraction probably comes from the planets in our own solar system.

How many planets/moons in our solar system might be habitable or might once have been habitable when the solar system was younger (before they lost their atmospheres, when the young sun was not as hot, etc.)? List each one below and provide a one-sentence explanation of what evidence suggests that it might be (or might once have been) habitable. Some things to consider: greenhouse effects, atmospheric escape, tidal heating, the presence of liquid water, alternative liquid cycles.

Of these, how many developed intelligent life?

Use the information above to calculate the fraction of habitable worlds in our own solar system that developed intelligent life. Show/explain your work below and make sure your answer has a unit.

Factor 6: Fraction of Intelligent Species that Can Communicate

There are many ways to approach this one, all of them speculative. Let's take a unified approach, for which there will be many different answers in the class.

Since Earth is the only planet we know of with life, let's use the myriad species on Earth to estimate this factor.

What do you believe is an appropriate definition of intelligence?

Of the species on Earth, how many fit within your definition? List them below.

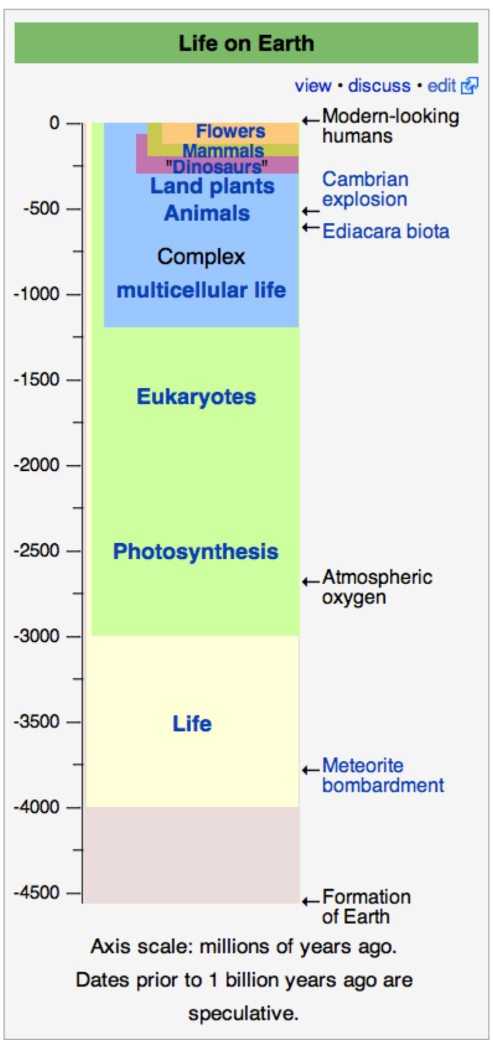
Of these species, how many of them developed the technology to communicate beyond Earth?

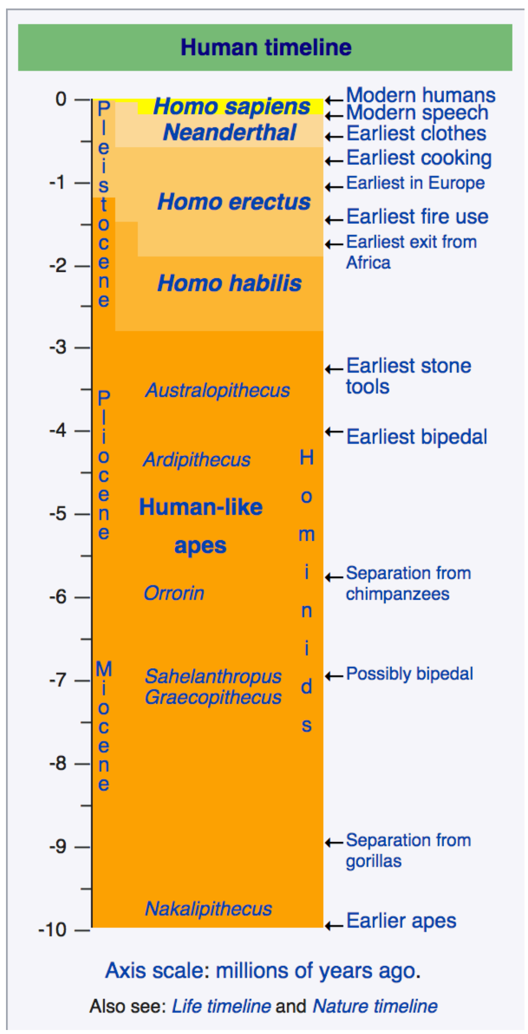
Put these answers together to create an estimate for the factor f_c. Show/explain your work below and make sure your answer has a unit.

Factor 7: Lifetime of an Intelligent, Communicating Civilization

Here again, we really only have life on earth to use as a data point from which to estimate, and our own species' lifetime has not yet ended (thankfully).

Given the information in the two timelines below, how long have humans as a species been around, as a fraction of total amount of time since life first developed on Earth?





Humans first developed radio technology around 1900. How much longer do you think we'll be broadcasting signals to the cosmos? Make an 3-4 sentence argument below. Things you might consider: our increasing "radio quietness", the stability of our current civilization, the relative probability that a catastrophic natural disaster will occur and wipe out life as we know it?

Use your answer from above to estimate the factor L. Show/explain your work below and make sure your answer has a unit.