The scale of the Universe, and an inventory

- Space is big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space. – Douglas Adams

Truly, the universe is a large place. If we are to consider the possibility of life anywhere else in the universe, we have to open our mind up to the various possibilities. As part of this, we need to take stock of what is in the universe, and the scales that we deal with. A prerequisite for this is that we need to be able to use scientific notation, and the units that are common in astronomy. After we go through that, we'll discuss different scales.

Scientific notation

With a universe as big as it is, and with things in it as small as subatomic particles, we can't just write out numbers normally. For example, the farthest that light has traveled to reach us is 137,000,000,000,000,000,000,000,000 meters, whereas the radius of a proton is about 0.000000000000001 meters. Clearly, we need a less clumsy way to deal with such quantities!

That way is scientific notation. In some of the lectures, and in the homework, we'll run into usages of scientific notation. I assume that most of you are already quite familiar with it, but I include it here as a reference. For practice, you can't do better than going to http://janus.astro.umd.edu/cgi-bin/astro/scinote.pl, where you'll be able to work practice problems.

The basic idea is this. Suppose that you have a large number, like 34929000. Let's write this as 34929000.0 so that we have an explicit decimal point. How many places to the left must we move that decimal point so that it is just to the right of the first digit? Seven places. Therefore, $34929000.0 = 3.4929 \times 10^7$. The order of the digits remains the same, and now we have multiplied by ten raised to the power of the number of places we had to move it. As another example, the speed of light is 299792458.0 meters per second. How could we re-express this in scientific notation? We need to move the decimal point over by eight places, so $299792458.0 = 2.99792458 \times 10^8$ meters per second.

If you have a small number, like 0.000000793, then in a similar way you ask yourself how many places to the right you must move the decimal point so that it is just to the right of the first nonzero digit. In this case it is seven places, so $0.000000793 = 7.93 \times 10^{-7}$. As a physical example, the radius of a hydrogen atom in its ground state is 0.0000000000529 meters. We have to move the decimal point 11 places to the right to get it to the right of the 5, so this is 5.29×10^{-11} meters.

Arithmetic with scientific notation is straightforward. You just have to remember that when you multiply, you *add* the exponents but multiply the part in front normally. As an example, we know that $10 \times 100 = 1000$. In scientific notation, this is $10^1 \times 10^2 = 10^3$. Note the *addition* of the exponents; if we multiplied the exponents we would get the incorrect answer that $10^1 \times 10^2 = 10^2$. For a more complicated problem, what is $(2 \times 10^2) \times (3 \times 10^3)$? Remembering that the exponents add, the final exponent has to be $2 + 3 = 5$. The parts in front, however, multiply normally, so they come to $2 \times 3 = 6$. Our final answer is therefore $(2 \times 10^2) \times (3 \times 10^3) = 6 \times 10^5$.

For division, you *subtract* the exponents but divide the part in front normally. For example, $1000/100 = 10$, or in scientific notation $10^3/10^2 = 10^1$. Note again that our final answer is $3 - 2 = 1$, not $3/2$. What about $(6 \times 10^5) / (3 \times 10^3)$? Again, the exponents are subtracted, so we get $5 - 3 = 2$ and not $5/3$. The parts in front divide normally, giving $6/3 = 2$. Therefore, our final answer is $(6 \times 10^5) / (3 \times 10^3) = 2 \times 10^2$.

For addition and subtraction, you need to remember that these proceed ordinarily *if* you have the same exponent, so you should adjust the expressions accordingly. For example, how would you figure out $3 \times 10^3 + 2 \times 10^2$? The explicit steps are

$$\begin{aligned} 3 \times 10^3 + 2 \times 10^2 &= 3 \times (10^1 \times 10^2) + 2 \times 10^2 \\ &= (3 \times 10^1) \times (10^2) + 2 \times 10^2 \\ &= 30 \times 10^2 + 2 \times 10^2 \\ &= (30 + 2) \times 10^2 \\ &= 32 \times 10^2 \\ &= (3.2 \times 10^1) \times 10^2 \\ &= 3.2 \times (10^1 \times 10^2) \\ &= 3.2 \times 10^3 \ . \end{aligned} \tag{1}$$

Notice how we convert back and forth. Similarly, you can show that $3 \times 10^3 - 2 \times 10^2 = 2.8 \times 10^3$.

Units in Astronomy

Even with scientific notation, astronomers like to have at hand a number of specialized units that are reasonable measures of the systems in question. For example, we could indicate the masses of stars in units of kilograms. However, it is more convenient to give their masses in units of the mass of the Sun, and to remember (or have in some reference) that the Sun's mass is about 2×10^{30} kg. We could measure distances to other stars in meters, but again that is not well matched to the actual distances. Instead, distances are measured in units of parsecs. One parsec is about 3.086×10^{16} meters, and is the distance that light in a vacuum travels in about 3.26 years. There is also, of course, the light year, which is 9.46×10^{15} meters, but parsecs are preferred by astronomers because they are more directly related to observations (in particular, they relate to a measure of distance called parallax). With scientific notation in hand and a list of such constants (I don't expect you to memorize these numbers!), it is straightforward to convert back and forth.

Armed as we now are, we can start surveying the universe. We'll do this by moving outward: planets, stars, galaxies, and the universe itself.

The Solar System

Our Solar System is the one place in the universe that we know absolutely can support life! Therefore, as we go through this course, please have in the back of your mind the question of whether you think we are extremely special in this respect (e.g., having many unusual properties that are crucial to life arising), or whether many systems are likely to be similar to ours.

The important occupants of our Solar System are:

- The Sun. This contains all but about 0.1% of the total mass in the Solar System. The Sun (like the rest of the Solar System) is about 4.6 billion years old, and is a star with somewhat above average mass. It is a pretty stable star, with flares that can affect our atmosphere a bit but that is a reliable source of heat and light. When it was younger its luminosity (a name for the energy per time that it puts out) was maybe 2/3 or 3/4 of what it is now.
- Mercury. The nearest of all planets to the Sun (it has an orbital semimajor axis of just 0.4 AU, where 1 AU [astronomical unit] is about 1.5×10^{11} meters and is the average distance of the Earth from the Sun). It is also the smallest of the major planets, and as a result has essentially no atmosphere. Views of its surface make it look a lot like the Moon, with many large craters.
- Venus. This planet orbits at 0.7 AU, and has a very thick atmosphere (100 times atmospheric pressure on Earth) made mainly of carbon dioxide. It has the highest surface temperature of any planet, even more than Mercury, because of the greenhouse effect of the carbon dioxide. It is about the same size and mass as the Earth, leading many breathless science fiction authors throughout the years to imagine it as a steaming jungle, but with no liquid water, rains of sulfuric acid, and a temperature hot enough to melt lead the prospects seem dim.
- Earth. Home sweet home! The only planet to have liquid water on its surface. It also has a moon that, although not the biggest in the Solar System, is by far the largest relative to its host planet (among the major planets).
- Mars. The red planet, and the host of even more breathless science fiction stories than Venus. Mars is only about 1/10 of the mass of the Earth, but being farther from the

Sun (1.5 AU) it does have a thin atmosphere (1/100 of the Earth's). Mars has ice caps made of both water ice and dry ice, and we've explored it with a large number of probes.

- Jupiter. The biggest planet by far, it has more mass than all other planets combined. It also has four large moons, so that even at a distance of about 5 AU from the Sun, making the region quite cold, Jupiter's effects on some of the moons (Europa in particular) may allow them to have liquid water under many kilometers of ice. Could there be life in those oceans?
- Saturn. Many people's favorite because of its beautiful rings, Saturn also has the large moon Titan. Titan isn't squeezed by Saturn the way that Europa is by Jupiter, so at about 10 AU from the Sun it's mighty cold. However, the Huygens probe took photos that suggest that there might be liquid methane on the surface. Could this support life?
- Uranus and Neptune. The two outermost major planets, these are close to twins of each other. Uranus is at 20 AU from the Sun, and Neptune is at 30 AU, so it's frozen out there. These planets are themselves very large (14 and 17 times the mass of the Earth, respectively), and Neptune has the large moon Triton (which has nitrogen geysers!), but life prospects seems somewhat dim at this time.
- Asteroids. The "main belt" of asteroids lie between Mars and Jupiter, and are basically really big rocks. The largest one, Ceres, is about 1000 km in diameter (the size of Texas), but the overwhelming majority that we've seen are just a few km across. Many of the asteroids are thought to be good fossil records of the beginning of the solar system. Their orbits sometimes cross that of the Earth and lead to occasional collisions, the most famous being the impact 66 million years ago that did in the dinosaurs and most other animal species on Earth.
- Comets and other small distant objects. Comets have long been feared as harbingers of doom, and even in modern times have inspired (if that's the right word!) cultists to join them by, er, shedding their bodily forms. It's probably safer to just appreciate them for what they are, which is small icy bodies that come from the very distant portions of the Solar System (maybe 1,000 AU to 100,000 AU away). We are also discovering many larger objects that are closer by. For example, Pluto, which used to be classified as a planet, is now a "dwarf planet", orbiting at 40 AU. Comets contain simple organic materials, and some people think that this might be a way that the starter molecules for life could have been delivered to Earth.

Extrasolar planets

Before 1993 (i.e., in all of your lifetimes), the only planets we knew about were in our Solar System. However, since that point various surveys have detected about 300(!!) planets orbiting other stars. I am proud to say that the first extrasolar planets were detected around a pulsar, but the rest are around ordinary stars. We'll talk in detail about these guys in a later class, but suffice it to say that it is currently impossible to detect an Earth-mass planet at an Earth orbital radius around another star. Techniques keep on improving, however, and within 10-20 years it is expected that these detections could become routine. In the meantime, the systems thus far discovered look very little like our Solar System: they often have giant planets closer to their host stars than Mercury is to the Sun, and in many cases the orbits are highly eccentric as opposed to the nearly circular orbits in our system. On the other hand, only a small fraction of stars have been surveyed, so it is not clear whether our system is typical or extraordinary.

Stars

When we start going out to other stars, the distances get immense. The closest star to our Sun, Proxima Centauri, is 1.3 parsecs away. That's almost 10,000 times farther away than Neptune, the most distant major planet! Indeed, such huge gaps were one of the reasons that many people had difficulties accepting the Copernican universe; it just seemed like a waste of space.

Nonetheless, they really are that far away. Observations and theory have given us a pretty clear picture of the crude evolution of stars once they are on the "main sequence", which is the largest portion of their lives (during which they shine and support themselves by fusing hydrogen into helium). For the purposes of determining whether life could exist around various stars, the following facts are of relevance:

- Stars can extend from about 0.08 times the mass of the Sun to possibly 150 times the mass of the Sun, when they are born.
- The lower-mass a star is, the longer it is on the main sequence. Our Sun will last about 10 billion years total. Within a factor of about 10 of the Sun's mass (i.e., from mass $M = 0.1\ M_\odot$ to $M = 10\ M_\odot$), the lifetime scales roughly as $M^{-2.5}$. That means that a $0.1\ M_\odot$ star would live for a few trillion years, whereas a $10\ M_\odot$ star would live for only a few tens of millions of years.
- Low-mass stars have flares, just as the Sun does, except that the very low-mass stars have flares that are a significant fraction of their total energy output. That means that the illumination from such a star would go up and down far more than the Sun's does.
- When low-mass stars finish with the hydrogen in their cores, they expand to become red giants. For example, the Sun will grow until it is roughly 1 AU in radius, compared

with its current radius of roughly 1/200 of an AU. Such stars then sink back until they are "white dwarfs", about the size of the Earth but maybe 60% of the mass of the Sun. They then cool indefinitely. The red giant stage only lasts a few million years.

- When stars start out with at least $M = 8\ M_\odot$, they become giants, contract back to fuse helium to carbon, become supergiants, and so on. Eventually, they blow themselves to bits in supernovae. This is great for dispersal of many of the elements of life, but probably not such good news for any planets orbiting the star!

There are far more low-mass stars than high-mass stars. The Sun, for example, has a mass that is in the top 5% of the mass of all stars, and only about 0.2% of stars start out with more than 10 $M_\odot$.

The potential habitability of planets around stars of different masses is a matter of debate. High-mass stars live a short time, so life would have to evolve very rapidly. Low-mass stars give plenty of time, but their strong flares could prove challenging to life. My personal opinion is that since we can't observe other systems closely enough to determine if they have life (even microbial life), we shouldn't make statements about their habitability with too much confidence.

Galaxies

Galaxies are collections of stars, say between 10^7 of them and 10^{13} of them. Their typical sizes are measured in the thousands of parsecs. Our Milky Way probably has about 4×10^{11} stars, and we are about 7,000 parsecs from the center of the galaxy. Like anything else in universe, galaxies have undergone evolution with time. For example, when the universe was just a few billion years old (as opposed to its current 13.7 billion year age), collisions between galaxies were more common than they are now. The stars are so far apart that even when two galaxies of 10^{11} stars each collide, it would be unexpected if even one pair of stars hits directly. However, there is a lot of interstellar gas and dust in galaxies. This has low density (and I mean *really* low, as in typically about 10^{-21} the density of air!!), but there is so much of it that the gas/dust of one galaxy collides with the gas/dust of another. This can do spectacular things like produce a burst of star formation or feed the supermassive black hole that is at the center of all the large galaxies we've been able to examine so far.

Some people feel that life could only evolve at certain distances from the center of a galaxy. Too close to the center (e.g., 3,000 parsecs!) and there are so many supernovae that we would get high levels of radiation and cosmic rays. Too far away (say, 12,000 parsecs) and not enough heavy elements would be present to allow for the formation of solid planets like the Earth. Is this true? Again, I think we should be cautious about drawing definite conclusions at this point. For all we know, creatures at 1,000 parsecs from the center of our galaxy might require a certain level of radiation to exist, and they might be arguing that life could not possibly evolve 7,000 parsecs from the center!

There are, in any case, around 10^{11} galaxies in the observable universe, which is an amazingly large number. Multiplying this by the number of stars per galaxy gives something like 10^{20-21} stars total, any one of which could potentially have planets. This is more, by a large margin, than the number of sand grains on all the beaches on the entire Earth.

The universe

The universe has an age of 13.7 billion years (1.37×10^{10}). By one measure, then, the size of the observable universe is 13.7 billion light years. However, it appears that the totality of all there is (call it the cosmos) is at least significantly larger than what we see, and indeed could actually be infinite. We'll deal with some of the mind-boggling consequences of that in a later lecture. However, as we'll see in the next two lectures, the development of the universe from a hot, dense, nearly uniform phase early to its current cold, tenuous, structured situation has implications for when life might possibly have formed.