Lab 1: Orders of Magnitude, Distances, and Scales in the Universe

Today we'll explore some fundamental concepts used in astronomy. Astronomy is a field of extremes, and today we learn how to accurately quantify them. The goal of today's lab is to give you an understanding of how far away many astronomical objects are, and how the sizes of objects compare with the distance between them.

1 Scales of the Universe

1.1 Orders of Magnitude

Scientists use orders of magnitude to describe the sizes of various objects. In many cases, it is not necessary or practical to know an object's precise size. Its order of magnitude gives you an idea of how large it is. Strictly speaking, the order of magnitude of a value is the "power of ten" that is closest to the value. Although the Sun's radius is $695,000,000$ m, it's enough to know that its radius is *of order* 10^9 m.

I gave the Sun's radius with many zeros in the number, but we can write it in a more compact way by using scientific notation. To write a number in scientifc notation, find the first non-zero digit in the highest place (the left-most place; in this case it's the 6), and put the decimal point after that digit. Then count how many places you move the decimal place, which gives you the power of ten (in this case it's 8; convince yourself that this is true). If you move the decimal place left, the power of ten is positive. If you have to move the decimal place to the right (i.e. the number is less than 1), then the power of ten is negative. We can then say that the Sun's radius is 6.95×10^8.

While it's tempting to take the power of ten given in scientific notation as an object's order of magnitude, be careful. You need to round the number to the nearest power of ten, and in some cases, the nearest power of ten is the next one up. This is true for the Sun's radius - the power of ten used in scientific notation is 8, but since 6.95×10^8 rounds *up* to $10 \times 10^8 = 10^9$, the order of magnitude is actually 10^9.

For practice, find the order of magnitude of the following. Don't forget to include the unit!

1. **The Bohr Radius**, or the size of a hydrogen atom, 5.3×10^{-11} m
2. **The Empire State Building** 358 m
3. **The Universe** 4.32×10^{26} meters
4. **Two Years** 730.5 days
5. **The Hubble Space Telescope** 11,110 kg

1.2 Unit Conversions

Now look at some measurements that are *not* given in meters. To find their orders of magnitude, you'll first need to convert the value from the given units to meters.

Centimeters, inches, miles, and meters are examples of different units. When reporting a measurement it is very important to include the unit. Every number we will deal with in this lab represents something and requires a unit. Class is not 3 long - it is 3 *hours* long; the Brooklyn Bridge is not 1.13 long - it is 1.3 *miles* long.

To convert units, it's best to multiply the value by a fraction that is equal to one: 1 year/365 days, 12 inches/1 foot, etc. Sometimes, it may take several steps to reach the unit you want. For example, to convert 2.3 years to hours:

$$2.3\ years \left(\frac{365\ days}{1\ year}\right)\left(\frac{24\ hours}{1\ day}\right) = 20148\ hours \approx 10^4\ hours \tag{1}$$

In the following problems, convert the given values to meters, then give the order of magnitude. Use the table given below.

1. **Humans** Let's put it at 5'9", or use your own height if you wish.
2. **Distance from the Sun to the nearest star** 4.243 ly
3. **One Mile**
4. **The radius of the Earth** 6,371 km
5. **The Hubble Space Telescope (length)** 43.5 ft

1.3 Order of Magnitude Differences

Orders of magnitude are great for making (rough) comparisons. The Sun is about 10^6 times larger than the Earth, or six orders of magnitude larger. Saying "New York City has a population an order of magnitude greater than North Dakota" means "New York City's population is about 10^1 times the population of North Dakota".

To calculate the order of magnitude difference between thing A and thing B, you divide their orders of magnitude (OOM):

$$\frac{OOM(A)}{OOM(B)} \tag{2}$$

Remember that when you divide two of the same number with different exponents, you simply subtract the bottom exponent from the top exponent:

$$\frac{10^x}{10^y} = 10^{x-y} \tag{3}$$

1. The distance from Earth to the Sun is called an Astronomical Unit (AU). What's the order of magnitude difference between our distance from the Sun and the radius of the Earth?

2. What's the order of magnitude difference between Earth's distance from the Sun and the distance to the nearest star?

3. Estimate the order of magnitude difference between the length of the hallway and the thickness of a human hair. You can use a ruler to measure your hair, but you may not measure the hallway. Make reasonable assumptions in whichever units you wish, and convert those to meters. Show your work.

1 of these	**= this many of these**
1 inch (″)	2.54 centimeter (cm)
1 meter (m)	100 cm
1 kilometer (km)	1000 m
1 foot (′)	12″
1 mile	6285′
1 Astronomical Unit (AU*)	1.49×10^8 km
1 light-year (ly)	9.46×10^{12} km
1 light-year (ly)	63241 AU

*1 AU = the distance from Earth to the Sun

1.4 Powers of Ten

We're going to watch a short movie on powers of ten (`https://www.youtube.com/watch?v=0fKBhvDjuy0`).

1. Why is it useful for scientists to use scientific notation and orders of magnitude when describing things in the universe?

2 Scaling the Solar System

2.1 Estimating Sizes

How good is your intuition for astronomical sizes? Write down your best estimate for the relative sizes of solar system objects. Give concrete examples (swimming pool, grapefruit, grain of sand, Manhattan...). I'll only be grading this section for completeness, not accuracy, but you'll see how accurate you were at the end of lab!

1. If Earth is the size of a penny, how big is the Sun?

2. On the same scale, how big is Jupiter?

3. If the Sun is the size of a basketball, how big is Jupiter?

4. On the same scale, if the Sun is here in Pupin, where is the nearest star?

2.2 Setting the Scale

Now we'll set up a scale model of the solar system with the Sun the size of a basketball (25 cm in diameter). Download the table "Solarsystem_sec2_2.xls" from files.

1. What is the diameter of the Sun in km? (see the attached table)
2. Now set up the scale factor, F. A basketball is F times SMALLER than the Sun, or

   $$R_{Basketball} = F \times R_{Sun}$$

   (Don't forget to convert your units!)
3. On this scale, what's the distance between Earth and the Sun?
4. Title one of the attached tables so that it's clear what scale you're using.
5. Fill out the table to calculate the sizes of and distances between Solar System objects on this scale. Make sure there's at least one clear example of your calculations in your notebook, but you don't have to show every calculation if you don't want to.
6. Try to come up with real-world objects that are about the size of each object. Bonus: scale the Moon's size and its distance from Earth, and scale Saturn's ring system. (You may need to do some online research for this one)
7. Draw circles in your notebook at the right scale for each planet, or trace an object that's the same size.

2.3 Setting a different Scale

Now we'll set up a scale model of the solar system with Earth the size of a penny (19 mm). Repeat the steps in the previous section using another blank table, but use Earth for question 1. Don't forget a title for your table, and be careful with units! Finding real-world objects should be a little easier this time.

3 Conclusions

1. Compare your initial estimates from Section 2.1 to your calculations in Section 2.2 - how close were you?

2. How does the the size of the planets compare to their distances from the Sun? What about the size of the Sun compared to the distance of the nearest star?

3. Is the universe mostly made up of stars and planets, or empty space? Explain your answer in one paragraph.

4. Do you have any comments or questions?
   (This is a trick question, because to get credit for this you have to answer yes! If you understood the lab perfectly, then try to come up with a further application of these ideas, or tell me which part of the lab you liked best. If something was particularly confusing, please tell me!)