Homework 2: explore the Legacy Survey

Due: Wednesday October 13th 2020, at class time

In this exercise you will be exploring a region of the Universe by viewing the released data of the Legacy Survey, a combination of three photometric surveys that imaged a large fraction of the sky in several optical filters.

Go to legacysurvey.org. Here you can visualize any part of the sky that has been observed in this survey. It is not all the sky, but it includes nearly half of all the sky. Explore the possibilities that the viewer gives you to observe the Universe. Find some nearby galaxy, scroll around, explore the sky at your leisure. Do not be bothered by the horizontal streaks that bright stars cause due to electrons spilling in the electronic camera pixels when very strong light intensity causes saturation.

After some exploring, pick up some random object. It is your choice. You can pick a bright nearby galaxy, or a very faint object, but make sure it is an extragalactic object (do not pick a star, nebula or globular cluster that is part of the Milky Way). Then write a short essay about this object. Does it have a catalog name? Does it have a measured redshift? What type of galaxy is it? Is it a regular galaxy in dynamic equilibrium or is it perturbed by some interaction? Is it part of a cluster of galaxies? Are there objects around it that form a galaxy group or galaxy cluster at a very similar redshift?

If you have picked a faint galaxy, chances are good that you are the first human being in all history that takes notice of this particular galaxy. These released data contain images of hundreds of millions of galaxies. The images have been received by a telescope, recorded by an electronic camera, and stored in computer memories, and now they are being made available over the internet for all humanity to watch. But because there are so many galaxies, most of them have actually never been consciously observed and noticed by a human being. So in a way, you can say you have now discovered a new galaxy!

Write your essay about the object you have focused on, with maximum length of one page or about 400 words. In addition to the above questions, try to say what you can from the data you can collect. Give the coordinates, flux (in terms of magnitudes in different bands), redshift, angular size, and morphological type.

If the galaxy has a known redshift, calculate its luminosity and its actual size, in parsecs or light-years. Give the luminosity in solar luminosities, in the photometric band that the flux has been measured. Given the luminosity, say how many stars the galaxy probably contains. Calculate the age of the Universe when the galaxy emitted the light you are now observing. Do these calculations in the context of the now standard model of cosmology: flat space with $\Omega_{m0} = 0.3$ and $\Omega_\Lambda = 0.7$ (you can neglect radiation at the low redshifts where we observe galaxies). If it does not have a known redshift, do the opposite: estimate the likely luminosity of the galaxy if its morphology and environment tells you whether it is a very massive object or a dwarf galaxy, or from the photometry that you have available, or assume it has the same luminosity as the Milky Way if you have no other clue, and then do the inverse: compute what its redshift should be so that it has this luminosity, given the observed flux.

In the site legacysurvey.org, you have the sky coordinates where your cursor is pointing in a little window, in right ascension and declination (equatorial spherical coordinates). There are catalogs where you can figure out the object you are looking at with these coordinates, such as SIMBAD or the SDSS catalog, which you can find in the internet. Many of these catalogs have a direct link from legacysurvey.org.

Among all the essays, I will select a few to be discussed in class on November 12th, after all students have had a chance to look for these objects and explore them.

Some notes on astronomical magnitudes as a measure of flux

The brightness of stars is usually given in terms of astronomical magnitudes. The magnitude system has its origin in ancient astronomy, where stars visible to the naked eye were classified from first magnitude (for the few brightest stars in the sky) to sixth magnitude (the faintest visible ones). In modern times, astronomers realised the response of the human eye to brightness of a star is close to logarithmic, so that roughly the same factor in brightness separates one magnitude from the next. This factor was determined to be roughly a ratio of 100 in brightness for every 5 magnitudes, or a factor $100^{1/5} \simeq 2.512$ for every magnitude. This has led to a scientifically precise definition of magnitudes as the logarithm of light flux in a certain photometric band.

Magnitudes can be normalized in different ways: traditionally they were normalized to make the magnitude of the star Vega to be zero on all bands, but at present the system of AB magnitudes is more useful, in which the normalization is fixed in terms of physical units of flux.

A photometric band is defined by a filter window $W(\nu)$, which is the fraction of photons at each frequency ν which are detected and counted. The flux in a band B from a source that has flux per unit frequency $f(\nu)$ is

$$f_B = \frac{\int d\nu W_B(\nu) f(\nu)}{\int d\nu W_B(\nu)} \ . \tag{1}$$

In the AB system, the apparent magnitude in band B is

$$m_B = -48.6 - 2.5 \log_{10}[f_B/(\text{cgs unit})] \ , \tag{2}$$

where f_B is expressed in the cgs unit of $\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}$.

As an example, we calculate the apparent magnitude of a source from which we receive 1 photon per second per cm^2, over the band between wavelengths 4500 Å to 5500 Å (roughly the human eye high sensitivity band at night). This corresponds to frequencies of 6.66×10^{14} Hz and 5.45×10^{14} Hz, respectively, so the frequency width of the band is $\Delta\nu = 1.21 \times 10^{14}$ Hz. We can take the energy of a photon in the middle of the band, $h\nu = 4.01 \times 10^{-12}$ erg, to infer a flux $f_B = 3.31 \times 10^{-26}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}$. The apparent magnitude is

$$m_B = -48.6 - 2.5 \log_{10} f_B = 15.1 \ . \tag{3}$$

A star of 6th magnitude has a flux that is larger by $100^{(15.1-6)/5.} = 4350$, so the faintest light the human eye can see is when it receives about 2000 photons per second if the open pupil has about 0.5 cm^2 of area. The human eye has a response time of about 0.1 seconds, so it can detect light when it is getting about 200 visual photons from a point source every tenth of a second (assuming a low sky background light, meaning that you are far from any city lights so that your limit is the star light intensity and not the contrast with the sky).

Absolute magnitude is defined as the apparent magnitude that a source would have if it were at a distance of 10 parsecs. In the absence of any dust absorption, the absolute magnitude M is related to apparent magnitude m as

$$M = m - 5 \times \log_1 0 \left(\frac{d}{10\,\mathrm{pc}} \right) . \tag{4}$$

It is generally useful to express luminosities as a multiple of the luminosity of the Sun. For this, it is useful to have the absolute magnitude of the Sun in various bands that are often used in astronomy. The following are the absolute magnitudes of the Sun in the ugriz SDSS bands covering the optical spectrum from roughly 3000 Å to 10000 Å (see Blanton et al. 2003):

$$u = 6.80\,; \qquad g = 5.45\,; \qquad r = 4.76\,; \qquad i = 4.58\,; \qquad z = 4.51\,. \tag{5}$$

For example, the Sun at 10 pc has magnitude $g = 5.45$, a star of $1L_\odot$ in the g-band at 1 kpc has magnitude $g = 15.45$, and a star of $100L_\odot$ in the g-band and at 1 kpc has magnitude $g = 10.45$.

A final informative note: to compute the luminosity in solar luminosities once you know its apparent magnitude, you can use the luminosity distance to a given redshift. This luminosity is actually being computed in a wavelength band that is not the same as the one used for the observation, but in a band that is redshifted from the source emitting frame to the observer frame. So, if you look at different galaxies, the luminosity you are obtaining is for a band that depends on their redshift. If you wanted to calculate the luminosity in the same band in which the observation is done for all galaxies, you would then need to introduce another correction that is called "K-correction" in the specialized language of observational cosmology. You do not need to get into this detail and you can ignore this for this homework.