Astronomy 400B Lecture 3: Intro to Galaxies and Cosmology

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1 Galaxy Classification

Galaxies display a rich variety of morphologies, shapes, sizes, colors, and luminosities. Based on these bulk properties, astronomers have tried to develop classification schemes that group galaxies that may have similar formation mechanisms. The most famous classification scheme is owes to *Edwin Hubble*, and is sometimes called the *tuning fork*.

See Figure 1.11 of Sparke and Gallagher

The Hubble scheme separates galaxies primarily into *ellipticals* (aka early type) and *spirals* (aka late type), with an intermediate grouping called *lenticulars*.

Ellipticals, also called *spheroidals*, are typically massive galaxies with stars on non-circular orbits and with low gas content. Ellipticals tend to be red, old, and lack large amounts of on-going star formation. The largest ellipticals, called cD galaxies, are located at the center of clusters of galaxies. Ellipticals are classified with E, followed by a number that reflects the ratio of the semi major to semi minor axes. There are also *dwarf elliptical* (dE) and *dwarf spheroidal* (dSph) galaxies, that have lower mass. We now think these classifications represent a mass sequence rather than an evolutionary sequence.

Spirals are disk galaxies, typically containing blue, young stars, on-going star formation and lots of gas. Spiral galaxies are classified based on the prevalence of their bulge, with Sa galaxies having large bulges and Sd galaxies having very small bulges. We separately classify *barred spirals* based on the presence of a noticeable bar feature. Again, the size of the bulge defines the range from SBa to SBd. The Milky Way is probably Sc or Sbc, while Andromeda is an Sb galaxy. These classifications also represent a mass sequence rather than an evolutionary one. On the low mass end, there are Sm and SBm galaxies, as well as the *dwarf irregular* (dIrr) systems that are star forming but do not necessarily have well-defined disks. The "m" in Sm and SBm refer to *Magellanic* spirals, with the prototype being the LMC.

S0 galaxies (the lenticulars) are systems that are mostly a bulge with a subdominant disk.

The early type vs. late type nomenclature was originally mean to suggest an evolutionary sequence from ellipticals to spirals. Instead, we know think that ellipticals form from spirals in galaxy mergers that disrupt the well-defined circular orbits of spirals into the disordered orbital structure of ellipticals.

2 Galaxy Catalogues

Very influential in the discovery and naming of large nearby galaxies were

1. The Charles *Messier* catalogue from 1784 of 109 objects that looked "fuzzy" in small telescopes. Some of these objects were nebulae, some were globular clusters, and some were galaxies. Famous Messier objects include the Andromeda galaxy M31, the Triangulum galaxy M33, the M51 disk galaxy merging with a spheroidal, and the M101 Pinwheel Galaxy.

2. In 1888, 1895, and 1908, the *New General Catalogue* contained more than 7000 extended objects including many galaxies. The catalogue was created by Dreyer, and Caroline, William, and John Herschel. The NGC catalogue overlaps with the Messier catalogue (e.g., Andromeda is NGC 224).

3. Other modern catalogues include the *Third Reference Catalogue* by de Vaucouleurs and the *Uppsala General Catalogue* by Nilson that enumerates many galaxies in the UGC system.

3 Galaxy Surface Brightness

A galaxy with luminosity L at a distance d away will have a flux $F = L/(4\pi d^2)$. If the galaxy has a physical size Δx in the plane of the sky and an angular size $\theta = \Delta x/d$, then the surface brightness I will be

$$I \equiv \frac{F}{\theta^2} = \frac{L/(4\pi d^2)}{\Delta x^2/d^2} = \frac{L}{4\pi \Delta x^2} \tag{1}$$

Unless cosmological effects come into play, the surface brightness is independent of distance d. The units of surface brightness are often given in mag arcsec^{-2}, such that a square arcsecond area of the galaxy has the apparent brightness of an object with the same magnitude. Sensible astronomers also use $L_\odot \mathrm{pc}^{-2}$. Central regions of galaxies reach $I_B \approx 18$ mag arcsec^{-2}, while the outer regions of disks are typically $I_B \approx 25$ mag arcsec-2. The radius of the isophote of 25th B-band magnitude, R_{25} is used as a proxy for galaxy size, as is the *Holmberg radius* at the 26.5th magnitude isophote.

4 Sky Brightness

The sky is bright! In full moon, the sky is brighter than 20mag arcsec^{-2} in the optical and about 13mag arcsec^{-2} in the infrared. Most of the infrared sky brightness comes from spectral lines like OH in the atmosphere. Space is typically $3-4$mag arcsec^{-2} fainter in the optical and about 9mag arcsec^{-2} fainter in the near IR. For observations in the infrared, space can't be beat.

5 Galaxy Luminosity Function

We can count the number density of galaxies as a function of their luminosity, and we appropriately call this distribution the *luminosity function*. The galaxy luminosity function has been found to have a shape close to a parameterized form called the *Schechter* function (after Paul Schechter). The Schechter function provides the number density of galaxies in a differential luminosity bin dL as

$$\Phi(L)dL = \phi_\star \left(\frac{L}{L_\star}\right)^\alpha \exp\left(-\frac{L}{L_\star}\right)\frac{dL}{L_\star} \tag{2}$$

where $L_\star$ is a characteristic luminosity of galaxies and $\phi_\star$ is a typical abundance. Below $L_\star$, the luminosity function is a power law, and above $L_\star$ the abundance of galaxies drops exponentially. Sometimes, astronomers will use $1+\alpha$ as the power law exponent, so beware!

See Figure 1.16 of Sparke and Gallagher.

It happens to be the case that $L_\star \approx 2\times 10^{10} L_\odot$, which is close to the luminosity of the Milky Way. The typical abundance of galaxies is $\phi_\star \approx 7\times 10^{-3}\mathrm{Mpc}^{-3}$. The faint-end slope of the 2DF luminosity function is $\alpha = -0.46$. Defined as in Equation 2, the number of galaxies diverges as $L \to 0$ if $\alpha < -1$.

The total luminosity density provided by galaxies can be found by integrating Equation 2 as

$$\rho_L = \int_0^\infty \Phi(L) L dL = \phi_\star L_\star \Gamma(\alpha+2) \tag{3}$$

where Γ is the Gamma function, which for an integer n is $\Gamma(n) = (n-1)!$. It turns out that $\Gamma(1.5) \approx 0.886227$, so we have that $\rho_L \approx 1.25\times 10^8 L_\odot \mathrm{Mpc}^{-3}$.

6 Galaxies Trace the Universal Expansion

Galaxies are great because they are bright and easy targets for measuring spectra. By measuring spectra we can determine the redshift from identified spectral lines whose rest wavelengths are known. The redshifts can be converted into line-of-sight velocities v. Sensibly, in 1929 Hubble plotted the velocities of about two dozen galaxies versus their distances (which were very wrong), and found that the recessional velocity increased linearly with distance as

$$v = H_0 d, \tag{4}$$

which is known as the *Hubble Law*. The factor H_0 is known as the *Hubble parameter* and typically has units of km s^{-1} Mpc^{-1}. Current best estimates are that $H_0 \approx 67$ km s^{-1} Mpc^{-1}. We often further parameterize the *Hubble parameter* in terms of

$$h = \frac{H_0}{100 \text{ km s}^{-1} \text{ Mpc}^{-1}}, \tag{5}$$

such that $h \approx 0.67$. Often people will just approximate and use $h = 0.7$. Distances found from velocities depend on h^{-2} and number densities will depend on h^3, and often you will encounter the following standard notations

$$R = r\ h^{-1} \text{ Mpc} \quad \text{(Distance)} \tag{6}$$

$$L = l\ h^{-2}\ L_\odot \quad \text{(Luminosity)} \tag{7}$$

$$V = v\ h^{-3} \text{ Mpc} \quad \text{(Volume)} \tag{8}$$

$$N = n\ h^3 \text{ Mpc}^{-3} \quad \text{(Number density)} \tag{9}$$

When you see these notations, you need to plug in the value of the Hubble parameter h to compute a "proper" number. For instance, the book has the local luminosity density as $\rho_L \approx 2 \times 10^8 h\ L_\odot$ Mpc^{-3}. For $h = 0.67$, the proper luminosity density is then $\rho_L = 1.34 \times 10^8\ L_\odot$ Mpc^{-3}. You will hear astronomers say "with little h" or "including little h" – and sometimes they mean they have or have not included little h!

6.1 Hubble Time

You may have noticed that H_0 has units of inverse time. We can define the *Hubble time* as

$$t_H = \frac{1}{H_0} = 9.78 h^{-1} \text{ Gyr} = 15 \text{ Gyr} \times \left(\frac{0.67}{h}\right). \tag{10}$$

If the Hubble Law held to time $t \to 0$, then $1/H_0$ would be the age of the universe since the Big Bang. But the universe does not expand at the same rate during its history, and $1/H_0$ is simply an approximate age of the universe (not bad, since the universe is about 13.8 Gyr old).

6.2 Peculiar Velocities

As one might imagine, the expansion of the universe is not the only physical process that might induce a line-of-sight velocity for a galaxy relative to us. For instance, the random motions of galaxies in a galaxy cluster can induce a substantial los velocity (~ 1500 km s^{-1}) that might change the measured redshift for the galaxy. We call the deviation of the los velocity from the Hubble law the *peculiar velocity* of the galaxy, and write

$$v = H_0 d + v_{\text{pec}}. \tag{11}$$

7 Critical Density

We will describe in future classes the dynamics of the expanding universe. For now, we will discuss some salient features of the universal expansion. An important quantity is the *critical density* ρ_{crit}, which describes the critical energy density that the universe must have to be geometrically flat. From the equations of general relativity, we can determine that the critical density is

$$\rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} = 1.9 \times 10^{-29}\ h^2 \text{ g cm}^{-3} \ = 2.8 \times 10^{11}\ h^2\ M_\odot \text{ Mpc}^{-3} \tag{12}$$

For a matter dominated universe with the critical density, the age of the universe is

$$t_{\text{u}} = \frac{2}{3H_0} \approx 10 \text{ Gyr} \times \left(\frac{0.67}{h}\right). \tag{13}$$

But our universe is dark energy dominated (see below)! This is useful nonetheless because it's an exact result. For our universe, we have to do an integral (later!) to determine the age of the universe in terms of the Hubble parameter.

8 Components of the Universe

Our universe is comprised of a variety of forms of matter and energy. Owing to general relativity, both matter and energy provide a source for gravity and so both effect the dynamical expansion of the universe. Here is a brief run-down of the different types of matter and energy in the universe:

1. *Baryonic (normal) matter.* We are made of *baryonic* matter, meaning that we are comprised of forms of matter that are ultimately made from three quarks (proton and neutrons). There are also enough electrons such that the universe is electrically neutral, but their mass is $\sim 2000\times$ less than the nucleons. Surprising as it may seem, the universe is only about $4-5\%$ baryonic matter!

2. *Radiation* There are a **lot** of photons in the universe! The energy density associated with the total cosmic microwave background and the extragalactic background light is quite small today ($< 10^{-4}$ of the total energy density). At early times the universe was actually dominated by radiation, but the fractional contribution of radiation to the total energy density declines dramatically with time.

3. *Dark matter.* Most of the matter in the universe is dark matter, which comprises about $\sim 25\%$ of the total energy density. Dark matter is non-baryonic, and likely consists of subatomic particles called *Weakly Interacting Massive Particles*, or WIMPs, that only interact through the gravitational and possibly weak nuclear forces. There are plenty of dark matter candidates from elementary particle theories, but dark matter has not yet been detected directly via experiment.

4. *Dark energy.* This mysterious component of the universe as a negative equation of state associated with it, such that a universe dominated by dark energy accelerates its expansion as its volume increases. We think that about 70% of the universal energy density is comprised of dark energy, and it is possibly in the form of a "cosmological constant", meaning that the dark energy density remains constant with time. Since the universe is expanding and the matter density declines with volume, the universe is becoming progressively more and more dark energy dominated as it expands. The result is that the universal expansion will continue to accelerate, likely without a meaningful bound (the expansion will infact eventually exceed the speed of light if the dark energy is a cosmological constant). There are natural ways of estimating the energy density associated with a cosmological constant from fundamental particle physics, but these methods overestimate the amount of dark energy by ~ 120 *orders of magnitude*(!; depending on how you count). Needless to say, even if the dark energy is a cosmological constant, we don't really know how to describe it in terms of a physical model.

5. *Curvature.* If the universe does not have the critical density, then there is a geometric curvature to the universe. There is an energy density associated with this curvature that can affect the dynamics of the universe, and if the universe is not flat then this curvature energy must reckon in the accounting for the time-dependent expansion rate. Fortunately (I guess), we think the universe is very close to flat, remarkably so, and most calculations will be performed assuming the curvature energy is zero.

9 The Scale Factor and Universal Expansion

Since the universe is expanding, it is useful to define a quantity called the *scale factor* $a(t)$ that relates the current separation $R(t_0) = r$ of objects to their separation $R(t) = r \times a(t)$ at a previous time. Defining $a(t_0) = 1$, and calling r the *comoving* separation, we can more easily compare physical (proper) length scales at different times. As one can infer, the Hubble parameter is related to the current rate of change of $a(t)$:

$$H_0 = \frac{1}{a(t_0)} \left.\frac{da}{dt}\right|_{t=t_0} = \frac{\dot{a}(t_0)}{a(t_0)} \tag{14}$$

where we'll use the dot notation to represent a time derivative. You can also infer that the Hubble parameter is time-dependent, such that $H(t) = \dot{a}(t)/a(t)$.

The expansion of the universe affects light that is traveling through the universe over an appreciable distance. As the universe expands, the wavelength of light will increase, leading to an induced redshift. If the galaxies recessional velocity is much less than the speed of light ($v \ll c$), then over the light travel time $\Delta t = d/c$ the ratio of the observed to emitted wavelength will be

$$\frac{\lambda_{\rm obs}}{\lambda_{\rm e}} = 1 + \frac{\Delta\lambda}{\lambda_{\rm e}} \approx 1 + \frac{H_0 d}{c} = 1 + H_0\Delta t = 1 + \frac{\dot{a}(t_0)}{a(t_0)}\Delta t \tag{15}$$

To find a more general relation, this equation can be rewritten to relate the rate of change in wavelength in terms of the rate of change of the scale factor as

$$\frac{\dot{\lambda}}{\lambda} = \frac{\dot{a}}{a} \tag{16}$$

We can integrate these equations over time

$$\int_{t_{\rm e}}^{t_{\rm obs}} \frac{\dot{\lambda}}{\lambda} dt = \int_{t_{\rm e}}^{t_{\rm obs}} \frac{\dot{a}}{a} dt \tag{17}$$

$$\ln \frac{\lambda(t_{\rm obs})}{\lambda(t_{\rm e})} = \ln \frac{a(t_{\rm obs})}{a(t_{\rm e})} \tag{18}$$

$$1 + z = \frac{\lambda(t_{\rm obs})}{\lambda(t_{\rm e})} = \frac{a(t_{\rm obs})}{a(t_{\rm e})} \tag{19}$$

This equation is the *cosmological redshift* formula that enables us to compute the redshifting of light from the universal expansion as it travels from distant objects to us. Note that the cosmological redshift may also be used as a short hand for time or relative scale factor. As $z \to \infty$, $t_{\rm e} \to 0$, and $a(t_{\rm e}) \to 0$. The most distant galaxies now known are at $z \sim 10$ and the CMB was emitted at $z \sim 1100$.

10 The Early Universe

From the Wein displacement law, we know that the peak emission wavelength of a black body varies inversely with its temperature. The wavelength of light in the universe will be redshifted by the cosmological expansion, so we expect that black body radiation filling the cosmos will have its temperature decline as $T \propto 1/a(t)$. A corollary of this relation is that at early times, the universe was filled with very hot, energetic radiation. Interacting photons with sufficient energies could produce matter–antimatter pairs of particles. Here's how it works – basically the typical energy of a photon in a radiation field of temperature T is

$$\mathcal{E} = 4k_{\rm B}T. \tag{20}$$

Roughly speaking, a pair of photons could produce a proton–antiproton pair if

$$k_{\rm B}T \gtrsim m_{\rm p}c^2 \tag{21}$$

where $m_{\rm p}$ is the mass of the proton. We typically talk about mass energies like $m_{\rm p}c^2$ in units of the *electron volt* (eV), which is the energy gained by an electron moving across a potential difference of 1V. For reference, an electon volt 1eV $= 1.6 \times 10^{-12}$ erg. The rest mass energy of the proton is $m_{\rm p}c^2 = 0.938272 \times 10^9$eV $=$ 0.938272 GeV. It turns out that this energy corresponds to a universal time of $< 10^{-4}$s when the universe had a temperature $T \gg 10^{13}$ K. So before this epoch, protons and antiprotons could be created in pairs freely. After this epoch, the temperature of photons were no longer high enough to produce the pairs and the only possible process was annihilation.

10.1 Baryon Asymmetry

A substantial problem in modern physics is explaining why, in the context of the above picture, there were somehow more protons that survived than antiprotons! That problem is called *baryon asymmetry* and it forms an important area of current fundamental physics research. The size of the asymmetry was only about one part in a billion.

10.2 Other Processes