ASTR 1120 Section 1 (3 credit hours): Spring 2006

SUMMARY OF KEY CONCEPTS: GALAXIES AND COSMOLOGY

Lecture #17 – textbook Chapter 20

We discussed **galaxies** – a galaxy is an island of stars held together as a single unit by gravity. A large galaxy, such as the Milky Way galaxy that the Sun is part of, contains around 100 billion stars. There are about 100 billion galaxies in the observable Universe.

Galaxies are observed to often live in groups or clusters of galaxies. There is no clear demarcation between these, but a group normally refers to a system with a handful of large galaxies while a cluster is a much richer structure sometimes containing hundreds of large galaxies. The Milky Way belongs to the Local Group – which also includes Andromeda, the nearest large galactic neighbor to the Milky Way.

An important distinction between stars and galaxies is that galaxies are separated by distances that are typically around 10 times the size of a galaxy. This means that galaxies are packed together relatively tightly, and as they orbit around under the action of gravity they often collide with each other. Those collisions lead to mergers, and allow large galaxies to grow by swallowing smaller ones. This is unlike the situation for stars – stars are extremely small compared to the typical separation between stars and as a result stars almost never collide.

Galaxies are classified based primarily on their appearance. The main distinction is between elliptical galaxies and spiral galaxies (the Milky Way is a spiral), with the latter being further divided into barred and unbarred spirals. Elliptical galaxies are smooth, `round', and rather featureless. They lack a lot of cool gas – and as a result are not forming stars today – and don't have spiral arms or dust lanes. Spiral galaxies are defined by their spiral arms, which can be prominent due to either recent star formation or dust lanes.

Irregular galaxies are another class – these have a disturbed morphology that is often the result of ongoing interactions or mergers with other galaxies.

Lecture #18

Hubble's Law relates the distance of a galaxy from us to its recession velocity. The law can be written as:

$$v = H_0 d$$

where H_0 is called Hubble's constant. This law is important… make sure you know what it means.

Hubble's Law requires measurement of the distances and velocities of distant galaxies. Distance is hard to measure, because a faint galaxy could either be intrinsically faint and (relatively) nearby, or very luminous and distant. In other words, measuring the apparent brightness tells us nothing about the distance (recall the inverse square law). However, for some sources – called standard candles – the luminosity is known independently (in the simplest case, the luminosity of some class of objects is *fixed*). In this case, the apparent brightness *does* tell us the distance.

White dwarf supernovae – triggered when a white dwarf star gains mass and exceeds the maximum mass a stable white dwarf can have – are excellent standard candles and the best way to measure distances to distant galaxies.

Velocities can be measured from the shift in the wavelengths of spectral lines caused by the Doppler shift (this is much easier than measuring distances). If a spectral line, observed on Earth to have a wavelength λ_{rest}, is seen at wavelength $\lambda_{\text{observed}}$ in the spectrum of a distant galaxy, we define the **redshift** z via $z = (\lambda_{\text{observed}}-\lambda_{\text{rest}}) / \lambda_{\text{rest}}$. Distant galaxies have large redshifts. For small redshifts, the redshift can be related to the recession velocity via a simple formula $v = cz$, where c is the speed of light.

Lecture #19

We discussed Olber's Paradox - `why is the night sky dark?'. In an infinite, static, everlasting Universe, every line of sight would eventually intercept the surface of a star, whose surface brightness is independent of the distance. So the whole sky would be the same brightness as the disk of the Sun! That this is not the case is the paradox. The resolution of the paradox lies in the fact that the Universe is neither static, nor everlasting.

The **Big Bang** is a theory of cosmology in which the Universe at early times was hot and dense. Over time, it has expanded and cooled. We observe the expansion as Hubble's Law – distant galaxies are moving away from us, at a rate that increases the further away they are.

Hubble's Law does *not* imply that there is a single `center' to the Universe, or that the Universe is expanding into something. Observers in other galaxies would determine the same law as we do. A good analogy for the expansion of the Universe is to think about what happens to dots painted on the surface of a balloon as it's blown up – each dot gets further away from every other dot with time.

We showed that the age of the Universe can be estimated in a simple way once Hubble's constant is known – in fact the age = $1 / H_0$ once H_0 is expressed in appropriate units. A high value of Hubble's constant means a young Universe, and vice versa. The observed value of Hubble's constant implies the Universe is about 13.6 billion years old.

Lecture #20 – textbook Chapter 19 (sections dealing with dark matter)

The luminous mass in a galaxy can be estimated by measuring the light from stars, and adding in mass in the form of gas that can be detected with radio telescopes. We can also estimate the total mass by studying the motion of stars and gas and applying Newton's Laws of motion, in particular the formula:

$$v^2 = \frac{GM}{r}$$

that we used previously to measure the mass of the black hole at the Galactic Center. In the context of a galaxy, the formula allows us to determine the mass M of the galaxy within some radius r if we can measure the velocity v of stars or gas at that radius.

This analysis is easiest to apply to spiral galaxies, which have a well-organized rotation of the stars and gas about the center. In most cases, the resulting rotation curve (velocity as a function of radius) is found to be *flat at large radius*. This is an important observation. It implies that there is more mass in spiral galaxies than can be accounted for by the observed stars and gas. This is called *dark matter* – matter which affects stars and gas via gravitational forces (this is how we infer it exists) but which does not emit much (or any) light or other observable radiation.

The dark matter appears to be distributed in a halo – a roughly spherical structure around the galaxy that extends beyond the luminous edges defined by the spiral disk.

Dark matter could be many things – baryonic dark matter (of which there are many examples e.g. low mass stars, or stellar remnants) that is made of the same stuff (neutrons and protons) as ordinary stars, or non-baryonic dark matter made up of some elementary particle that has yet to be directly discovered. By a process of elimination, most astronomers believe the dark matter is made up of a new elementary particle, and experiments to detect such a particle on Earth are underway.

<u>Lecture #21</u> – Chapter 22

Dark matter – unseen mass whose existence is inferred from its gravitational influence on stars and gas.

Dark energy – unseen `substance' that appears to be causing the rate of expansion of the Universe to be accelerating (the opposite of what gravity is expected to do).

In addition to the evidence from spiral galaxy rotation curves, additional evidence for the existence of dark matter comes from observations of galaxy clusters. Clusters are the largest gravitationally bound structures in the Universe, which means that they provide a fair sample of the cosmic inventory of ordinary matter and dark matter. The amount of dark matter in a galaxy cluster can be estimated in three independent ways:

(1) Measuring the velocities of galaxies and applying the same sort of analysis as for spiral galaxies (more mass – whether luminous or dark – means higher velocities for galaxies moving around within the cluster).
(2) Measuring the temperature of gas distributed smoothly in the cluster potential – more mass means a higher temperature. This gas is hot – often 10 million degrees or more – so it emits in the X-rays.
(3) Analysis of gravitational lensing – all mass in the cluster combines to deflect the light of background galaxies as that light travels through the cluster. The lensing distorts the images of background galaxies into rings, arcs and multiple images. The distortion can be measured and used to infer the mass.

The result is that on the scales of clusters (and, by extension, for the Universe as a whole), about 15% of the mass is in the form of ordinary matter (stars and gas), while the other 85% is dark matter.

Lecture #22 – Chapter 23

We discussed the evidence for the hot Big Bang. The basic idea is that Hubble's Law implies that the Universe was denser in the past. When a gas expands, it cools, so the Universe would have been hotter as well as denser at early times. At very early times, the temperatures would have exceeded any that can be attained in experiments on Earth today – so the early Universe acted like a huge particle accelerator.

As the Universe cools, starting from very high temperature, a critical moment arrives when the Universe is *first cool enough for atoms to form*. This moment is called *recombination*. Prior to recombination, the Universe contains a plasma (free electrons and protons) which is opaque to photons. After recombination, the Universe contains atoms (electrons bound to protons in hydrogen and helium atoms) and is transparent to photons. At recombination, photons that were previously trapped within the plasma are released – they then travel freely through the Universe without further interaction with matter and can be observed today as the *Cosmic Microwave Background (CMB)*. The CMB is made up of microwaves because the expansion of the Universe redshifts the radiation from the original red / infra-red (the type of radiation emitted when atoms form at T ~ 3000K) by a factor of more than a 1000.

The CMB is observed to have properties consistent with those expected from the Big Bang theory:

(1) It's thermal radiation – the type of radiation produced from opaque bodies. The temperature is 2.73K – the lowest naturally occurring temperature in the Universe.
(2) It comes from all directions on the sky – not clustered like stars and galaxies are.

In more detail, the CMB sky is not completely uniform:

(1) There is a large scale pattern caused by the motion of the Milky Way relative to the frame in which recombination occurred. This motion – a few hundred km per second – means that the CMB is Doppler shifted… it's a few thousandths of a degree hotter in the direction toward which our galaxy is moving, and cooler in the opposite direction.
(2) If this is subtracted, there's an even smaller pattern of ripples with hot and cool spots that are a few parts in 100,000 different from the mean temperature. These anisotropies are the seeds from which galaxies and clusters of galaxies formed – viewed when the Universe was only 380,000 years old!

Lecture #23

The Universe would have been hot enough for fusion reactions to occur within the first three minutes or so after the Big Bang. This era is called *nucleosynthesis*. Big Bang nucleosynthesis forms hydrogen, helium, and some lithium – the other 'heavier' elements are formed within stars.

We discussed the puzzle of why the Universe appears to be surprisingly uniform on very large scales (as evidenced by the distribution of very distant galaxies on scales much larger than clusters of galaxies, and especially by the uniformity of the CMB sky once the Galaxy's motion has been subtracted). This is a puzzle because *widely separated points on the sky have never been in contact with each other during the history of the Universe* according to the standard Big Bang theory (i.e. a light signal could not have had time to pass from one point to another). There's therefore no reason to expect them to have the same conditions.

The most plausible explanation advanced to explain this puzzle is called *inflation.* Inflation posits that at extremely early times (maybe only 10^{-38} s after the Big Bang), an enormous injection of energy expanded the Universe exponentially. The entire observable Universe derives from a tiny patch pre-inflation that was small enough to be in causal contact with itself. Quantum fluctuations within that small patch seeded the formation of galaxies.

Inflation predicts the relative strengths of different sized ripples in the CMB. Those predictions are in excellent agreement with recent observations by the WMAP satellite.

Lecture #24 – dark energy: review appropriate parts of Chapter 22