Please note: the regions in grey fonts are left over from last year. You may use them as a guide, but they are not yet updated for this course and may change!

I’ve spelled out the links to the slides explicitly, so you can cut and past them into your browser if you are having trouble clicking through automatically.

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   2.1  The wavelength and frequency ............................................................ 3
   2.2  The electromagnetic Spectrum ............................................................ 3
   2.3  Light and Temperature ................................................................. 4
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1 Introduction and Overview: The big picture

- Slides: “The Big Picture”
  [http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S1/S1.ppt](http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S1/S1.ppt)
• Go over 1st handout

Start Jan 7 Lecture
Assigned reading: Chapter 5

• Finish discussion these Slides: “The Big Picture”
  http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S1/S1.ppt

Start Jan 12 Lecture
Collect HW1, HW2 assigned on web

2 The nature of Light

2.1 The wavelength and frequency

Light has:
• Wavelength $\lambda$
• Frequency $f$

Key relationship:

$$\lambda \times f = c$$

$(c = 3 \times 10^8 \text{ m/sec})$

• Particle behavior: A single particle of light (Photon) has energy:

$$E = h \times f = \frac{hc}{\lambda}$$

where

$h = 6.626 \times 10^{-34} \text{ Joule} \times \text{sec}$

2.2 The electromagnetic Spectrum

• LIGHT & SPECTROSCOPY (Multimedia lesson from “Mastering Astronomy”, the web site associated with the textbook)
• Lecture demonstration of emission spectra using diffraction gratings and various lamps

• Tell helium story: The element Helium was discovered because some spectral lines observed from the sun did not match any observed (up until then) in the lab.

2.3 Light and Temperature

The blackbody spectrum: An object with a definite temperature and which does not reflect is called a “blackbody” (even though a blackbody can emit plenty of light!)

Blackbodies have there special properties:
• Emitted power per unit area:

\[ P = \sigma T^4 \]

\[ \sigma = 5.7 \times 10^{-8} \text{ Watts} \quad \text{m}^2 \times \text{K}^4 \]

(CP Math insight 5.2)

• The thermal spectrum depends only on \( T \). (Discuss fig 5.19/Image from multimedia presentations)
• Peak of spectrum has simple \( T \) dependence (CP Math insight 5.2):

\[ \lambda_{max} \approx \frac{2,900,000}{T \text{ (Kelvin)}} \quad \text{nm} \quad (0.1) \]

• Spectral lines can appear against a blackbody spectrum (Discuss figure 5.13),
• Slides http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S2/S2.ppt
• Discuss why the sky is blue and sunsets are red.
2.4 Doppler Shift

- Draw Picture (see also slides http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S2/S2.ppt, result:

\[
\frac{v_{rad}}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}}
\]

- \( \lambda_{shift} > \lambda_{rest} \) Increases when receding ("redshift")
- \( \lambda_{shift} < \lambda_{rest} \) Decreases when approaching ("blueshift")

Multimedia presentation from “MasteringAstronomy” on the Doppler shift.

2.5 Applications to Astronomy

- Galaxy rotation curves (Show PowerPoint slides http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S2/S2.ppt)

2.6 Review of Light Properties

- \( \lambda \times f = c \)
  - \( c = 3 \times 10^8 \text{ m/sec} \)

- \( E = h \times f = \frac{hc}{\lambda} \) where \( h = 6.626 \times 10^{-34} \text{ Joule \times sec} \)
- Spectral Lines characterize chemical elements.
- In Thermal Eqm, Emitted power per unit area =
\[ \sigma T^4 \]
\[ \left( \sigma = 5.7 \times 10^{-8} \frac{\text{Watts}}{\text{m}^2 \times \text{K}^4} \right) \]
(CP section 6.4)

- In Eqm: “Blackbody spectrum” (see figure 5.13)
- Doppler Shift

\[ \frac{v_{\text{rad}}}{c} = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \]

3 Cosmic Expansion

3.1 The cosmic distance Ladder

multimedia tutorial on “Mastering Astronomy” “Measuring Cosmic distance”

Discuss math insight 20.1 at the board:

\[ P_{\text{telescope}} = P_{\text{star}} \times \frac{A_{\text{telescope}}}{4\pi d^2} \]

apparent brightness = “flux” = “power/area”

\[ \text{flux} = \frac{P_{\text{telescope}}}{A_{\text{telescope}}} = \frac{P_{\text{star}}}{4\pi d^2} = \frac{L}{4\pi d^2} \]

There is further discussion in math insight 20.1, on page 641.

continuation of “Measuring Cosmic Distance” multimedia presentation
### 3.2 The Redshift
Discuss Galaxy redshift (slides http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S3/S3.ppt)

### 3.3 The Hubble Law
Multimedia Presentation “Hubble’s Law”
Blackboard discussion of $v = H_0 r$

\[
H = 65 \frac{\text{km/sec}}{\text{Mpc}} \approx \frac{1}{10^{10} \text{yr}}
\]

$1 \text{Mpc} \approx 3.3 \times 10^6 \text{ly}$

### 3.4 Further Discussion of the expanding Universe
*Implications* (Discuss “big picture” slides from introductory slides http://www.physics.ucdavis.edu/Cosmology/COS10/Notes/S1/S1.ppt)

- Simple behavior!!
- Independent of observer’s position (d=0)
- Finite age of the universe
  \[
  \approx 10^{10} \text{yr}
  \]

  Compare with ages of star clusters (two *completely different* kinds of physics!)
  It is amazing they agree.
  - Hot big bang, => connection with all energies of physics.
  - The Singularity: Infinite density 14 billion years ago => theory breaks down!
  
  This is the subject of current research.

“mastering astronomy tutorial: Hubble’s Law”

<table>
<thead>
<tr>
<th>Start Jan 26 Lecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading: Ch 23 (new material not covered on 1st midterm)</td>
</tr>
</tbody>
</table>
### 3.5 Hubble expansion from different points of view

<table>
<thead>
<tr>
<th></th>
<th>Object 1</th>
<th>Object 2</th>
<th>Observer</th>
<th>Object 3</th>
<th>Object 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (Megaparsecs)</td>
<td>-4</td>
<td>-2</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Velocity (along line of sight, in km/sec)</td>
<td>-200</td>
<td>-100</td>
<td>0</td>
<td>100</td>
<td>200</td>
</tr>
</tbody>
</table>

Rewrite from the point of view of new observer on object 3 (discuss methodology in class)

<table>
<thead>
<tr>
<th></th>
<th>Object 1</th>
<th>Object 2</th>
<th>Old Observer</th>
<th>Observer on Object 3</th>
<th>Object 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (Megaparsecs)</td>
<td>-6</td>
<td>-4</td>
<td>-2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Velocity (along line of sight, in km/sec)</td>
<td>-300</td>
<td>-200</td>
<td>-100</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>
3.6 Uncertainties in the Hubble Constant

The value of the Hubble constant:

⇒ Until very recently, the actual value of the Hubble constant was much more poorly known than the fact that the Universe obeyed the Hubble law.

⇒ The uncertainty came from an overall uncertainty in distance measures that would allow for points on the Hubble plot to clearly fall on a line, but with uncertain slope.

Here is an illustration of how that could happen:

We’ve learned that astronomers can use flux f (or “apparent brightness”) to measure distance if we know the luminosity $L$ according to the inverse square law of radiation (see p623):

\[ f = \frac{L}{4\pi d^2} \]

which gives

\[ d = \sqrt{\frac{L}{4\pi f}} \]

Suppose we have
Object  v (from doppler shift)  flux (Lsun/(Mpc)^2)  inferred distance for L=4piLsun
1  100  1   1
2  200  1/4  2
3  300  1/9  3
4  400  1/16  4
5  500  1/25  5

If the luminosity is $4\pi L_{\text{sun}}$ then you infer the distance given in the table using the above formula. (you would use $d = \sqrt{\frac{1}{f}}$) These points lie on a line which obeys $v = H d$ with $H=100 \text{km/sec/mpc}$

Suppose you think that you might be wrong about the luminosity of these objects, and they all really have a luminosity of $16\pi L_{\text{sun}}$. Then you would use $d = 2\sqrt{\frac{1}{f}}$ and get

\[
\begin{array}{cccc}
\text{v (from doppler)} & \text{flux} & \text{inferred distance for } L=16\pi L_{\text{sun}} \\
100 & 1 & 2 \\
200 & 1/4 & 4 \\
300 & 1/9 & 6 \\
400 & 1/16 & 8 \\
500 & 1/25 & 10 \\
\end{array}
\]

These points still lie on a line, but have $H=50 \text{km/sec/mpc}$. Thus, certain uncertainties *can* affect the overall slope, but not the fact that the data fall on a line.

**IMPORTANT.** Any data which obeys $v = H d$ is said to “obey the Hubble law” *regardless* of the value of $H$

**4 More discussion of the cosmic expansion**
4.1 The story of the “cosmological principle”

- Einstein wanted his theory of relativity to obey something called “Mach’s principle” (Mach’s principle is too advanced to discuss in this class, but, roughly speaking the idea is your theories of physics should be defined as much as possible in terms of physically observable things, as opposed to pure mathematics)
- People discovered that Einstein’s theory did not obey Mach’s principle
- Einstein changed the theory by adding the “cosmological principle”: The universe should look the same from the point of view of each observer
- This new constraint made allowed Einstein’s theory obey Mach’s principle.
- The cosmological principle also introduced the “Hubble Law” before it had been observed (because the Hubble Law is observer-independent).
- It is remarkable that the very philosophical thinking by Einstein and Mach (which is not very persuasive by modern standards) led to the right answer, even though there was not the slightest clue yet from data.

This topic “the cosmological principle” will not be on exams.

<table>
<thead>
<tr>
<th>Start Jan 28 Lecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collect HW3</td>
</tr>
</tbody>
</table>

4.2 Cosmic Expansion: Homework 3.x

Discuss Homework 3.X
Try
\[ v = H d^2 \]

(alternatively \( v = H d |d| \))

with \( H = 100\frac{km}{sec (Mpc)^2} \)

<table>
<thead>
<tr>
<th>Distance (Megaparsecs)</th>
<th>Object 1</th>
<th>Object 2</th>
<th>Observer</th>
<th>Object 3</th>
<th>Object 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>-400</td>
<td>-100</td>
<td>0</td>
<td>100</td>
<td>400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Velocity (along line of sight, in km/sec)</th>
<th>Object 1</th>
<th>Object 2</th>
<th>Old Observer</th>
<th>Observer on Object 3</th>
<th>Object 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-400</td>
<td>-500</td>
<td>-200</td>
<td>-100</td>
<td>0</td>
<td>300</td>
</tr>
</tbody>
</table>

Conclusion: Object 3 observer does not see the same \( v = H d^2 \) law.

Clarification: I filled out the second table using information from the first. In particular, I moved the zero point to observer 3, but preserved the same *relative* distances and speeds as given in the upper table. The point is that the table can *not* be produced using a \( v = H d |d| \) law with a zero point at observer 3.
The $v = Hd$ law is special, in that it looks the same for every observer.

5 The cooling universe and the formation of Nuclei
(See p 684-686 of the text)

All chemical elements are comprised of a positively charged nucleus surrounded by negatively charged electrons. The nucleus is made up of particles called protons and neutrons.

The expansion of the Universe tell us that in the past the universe was once very hot and dense. At high densities and temperatures, collisions are so energetic that the bonds that tie the electrons to the nucleus are easily broken by a typical collisions. That means the elements are “ionized” with the nuclei and electrons moving about independently.

At even higher temperatures (further in the past) typical collisions were so energetic that that the nuclei themselves were easily broken up, and the protons and neutrons traveled freely in the Universe, unbound from each other. This is the starting point of our story in this section. Physicists can use our knowledge of how protons, neutrons and nuclei interact to track the behavior of the universe as it passes from this early phase to a point where nuclei are stable and are not destroyed by collisions.

The so called “Weak Interactions” allow the conversion (both ways) between protons and neutrons. At the high temperatures phase, when there were only protons and neutrons the weak interactions created an equilibrium state where there were equal numbers of protons and neutrons. As the temperature dropped the weak interactions started favoring protons over neutrons and the fraction of protons started to increase.

Along the way, the universe reached a stated where it became possible to produce stable Helium (aka Helium-4, made of two protons and two neutrons). To understand why only Helium was stable at this stage; we inspect the following chart of nuclear binding energies (Figure 1). We see that it takes a lower amount of energy to break apart heavier elements into Helium. This energy is still available from the thermal energy, even though the (larger) amount of energy
required to break apart Helium is no longer thermally available. Thus helium is stable.

Figure 1

At this point, all the available neutrons are formed into Helium and the proportion of different chemical elements “freezes out”.

Note that the above story is based on detailed calculations that apply our knowledge of nuclear physics to the conditions that were present at the early stages of the Big Bang (and are too advanced to present in detail in a Physics 10 class).

The thing we can do is work out the proportion of Hydrogen to Helium. We take as our starting point that calculations show that the weak interactions have brought
the proton to neutron ratio up to 7:1 at the time of freeze-out. As discussed in class, we can draw a picture (with p=proton, n=neutron) that shows them present in a 7:1 ratio. Because we need two neutrons to make one Hydrogen, I show two 7:1 rows (in purple) in Figure 2. The green box in Figure 2 shows two protons and two neutrons. Since we are told all neutrons form Helium, we can count the green box as a Helium nucleus (made up of two p’s and two n’s). The remaining p’s remain as Hydrogen nuclei, so by counting objects in the picture, the ratio of Hydrogen to Helium is 12:1. However, astrophysicists care most about the proportion by mass. To determine that, we use the fact that protons and neutrons have essentially the same mass (taking the two masses to be equal is a fine approximation for us). Figure 2 shows red circles around groups of four particles. Each group has the same mass. Since there are three red boxes of Hydrogen and one red box of Helium, the ratio by mass of Hydrogen to Helium is 3:1 (in other words the percentage by mass is 75% Hydrogen, 25% Helium).

If the laws of physics (especially the weak interactions) were slightly different we might have started with a different proton to neutron ratio, giving the universe a very different proportion of chemical elements. This fact is very important in contemporary research since it allows us to test alternative theories. You will see examples of this in Homework 4.
6 The Cosmic Microwave Background (CMB)

6.1 “Freeze out” of photons

- Early times: Hot & Dense $\rightarrow$ opaque
- Later: Cool & Dilute $\rightarrow$ transparent (most light today travels many billions of lightyears without colliding.)
- Transition between these two states= “surface of last scattering”

Discuss how “surface of last scattering forms a sphere around any observer (closely related to HW5)
As we look back in space we look back in time. We see:

Light traveling from far away = from distant past

Long ago (about 14 Billion years) the Universe was so hot and dense it was opaque: The edge of the observable universe


<table>
<thead>
<tr>
<th>Feb 11 Lecture</th>
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</thead>
<tbody>
<tr>
<td>Collect HW5</td>
</tr>
<tr>
<td>HW6 and new reading assigned on web</td>
</tr>
</tbody>
</table>

See also background story here
wrap up CMB discussion

7 Gravity

7.1 Newton’s Laws of Motion

1- No net force => constant velocity
2- F=ma
3- Every force has equal and opposite reaction force (*Illustrate all these with wagon*)

### 7.2 The gravitational force

\[ F = G \frac{m_1 m_2}{r^2} \]

- Always Attractive
- "inverse square law"
  - \( G = 6.67 \times 10^{-11} \text{ nt} \cdot \text{m}^2 / \text{kg}^2 \)

Slides on physical laws.

### 7.3 Orbits


Main points:
- Fast objects can escape the pull of gravity,
- slow ones get "pulled in".
- An "orbit" is a special (but robust) balance between these two options

Here for my reference: From the surface of the Earth, escape velocity (ignoring air friction) is approximately

7 miles per second,
25,000 miles per hour.
Show and discuss “motion and Gravity lesson 1” and “orbits and Kepler’s laws lesson 1” on MasteringAstronomy

Important comment on Mass:
For falling objects, orbits, “independent of mass” is only an approximation. For example:

\[ p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \]

(draw illustration with M’s and “a” marked)

Can neglect \( M_2 \) if \( M_1 \) is much larger. Typical errors are around \( \frac{M_1}{M_2} \) (M(earth) = \( 6 \times 10^{24} \) kg)

7.4 Gravitational Collapse

- Competition between kinetic energy and gravitational force
- Collapse occurs best when there is a mechanism removing kinetic energy (such as radiating photons).
- With less kinetic energy gravity faces less competition as it tries to clump matter together.

8 Galaxies and Dark Matter

<table>
<thead>
<tr>
<th>Feb 18 Lecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return HW5</td>
</tr>
<tr>
<td>Collect HW6</td>
</tr>
<tr>
<td>HW 7 Assigned on Web</td>
</tr>
</tbody>
</table>

8.1 Intro

Discuss Cosmic Perspective Figs 19.1 and 19.2

8.2 Orbital Velocity Law
For a circular orbit, \( a = \text{radius} \)

\[ v = \frac{2\pi a}{p} \]

use the above two equations to get

\[ M_r = \frac{r \times v^2}{G} \]

for the mass inside radius \( r \) for circular orbits (Bennett p667, math insight 22.2)

### 8.3 Rotation Curves
Discuss “Detecting Dark Matter in Spiral Galaxies” (MasteringAstronomy Tutorial)

### 8.4 Studies of galaxies and dark matter

Slides on galaxies
Discuss galaxy formation via gravitational collapse, including image from the “Virgo Consortium”

#### Feb 23

- Discuss MT 2 review sheet

### 8.5 Special example problem & discussion related to HW prob 7.8
(Ch 22 prob 42)

\[ M_r = \frac{r \times v^2}{G} \Rightarrow v = \sqrt{\frac{G M_r}{r}} \]
Discuss part a. (all mass inside “concentrated at center”)

b):  
- What does “constant mass density” mean?  
  \[ M_r = \rho V_r \] where \( \rho \) is a constant and \( V_r \) is the volume inside radius “\( r \)”

- What does “zero mass density outside radius some \( r_* \)” mean?

c): What does enclosed mass proportional to distance mean?

Example problem:

Galaxy has typical galaxy rotation curve for \( r<30,000 \text{ly} \) and \( M_r = A r^2 \) for \( r \geq 30,000 \text{ly} \) (where “\( A \)” is a constant).

\[ M_r = A r^2 \] is the same as “\( M_r \) proportional to distance squared”

8.6 Dark Matter Candidates

Slides (S9)  

8.7 Dark matter and simulations of cosmic structure formation  
Images and movies from the Virgo consortium

8.8 Optional special topic (Negative specific heat)

Optional Special Topic: “negative specific heat” of gravity (not included Winter 2010).

- Positive specific heat \( \Rightarrow \) Take energy out and temp. decreases.
- Discuss in terms of ball rolling in \((1/r)\) shape bowl. (this mimic the force of gravity)
Gravitating systems: Radiating energy causes the remaining matter (that is still gravitationally bound) to heat up. (➔ Take energy out and temperature goes UP)

This is because when KE (thermal energy) is released, particles shift to new orbits that on average release more potential energy into kinetic energy.

Thus we say gravitating systems have “negative specific heat”. (➔ Take energy out and temperature goes UP)

NB: Negative specific heat of gravitating systems is a fun topic which we may not have time to cover in class. It is *not* part of the required material for the course (& will not appear on exams or homeworks). Feel free to ask about it during office hours if you are interested anyway.

Feb 25

| Return HW6 |
| Collect HW7 |

One more look at the Bullet cluster at the end of these slides:

**Cosmic Inflation**

8.9 **The cosmological Puzzles**

8.9.1 Flatness Puzzle

**Warm Up: Escape velocity**

If an object has velocity \( v \) with

\[ v \geq v_{\text{escape}} \]

than it can leave the earth (or other object) and never return. The speed “wins out” over the gravitational force which is trying to pull it back.

From the surface of the Earth, escape velocity (ignoring air friction) is approximately

7 miles per second,
25,000 miles per hour.
11100 m/s
40200 km/h

\[ \frac{1}{2} m v_{\text{escape}}^2 = \frac{G M m}{r} \]

Formula: 

Note that the mass of the object escaping, \( m \), drops out. The mass of the object being escaped from, \( M \), is assumed to be much larger than \( m \).

Given that initial speed, an object needs no additional force applied to completely escape Earth's gravity.
(See pp 132 of Bennett et al and MasteringAstronomy Applet: Cannonball Mass & Orbital Trajectory)

\( \Rightarrow \) End Warmup

The Universe: The Universe is expanding (flying apart) but gravity is trying to pull the matter back together.

Does the Universe have “escape velocity” from itself?

\[ \begin{array}{|l|}
\hline
\text{Mar 4} \\
\hline
\text{Return HW7} \\
\text{HW 9 assigned on web (due Thursday)} \\
\text{HW 8 due tuesday} \\
\hline
\end{array} \]

Answer defined in terms of “critical density” \( \rho_c \)

- Density: Mass/volume
- Average density of universe today \( \approx 10^{-29} \text{gm/cm}^3 \)
- If \( \rho \leq \rho_c \) the universe has “escape velocity” from itself, and will never “fall back” and re-collapse.
- \( \rho > \rho_c \) implies the universe has enough mass to slow down the expansion and eventually re-collapse.
- The value of the critical density is given by:

\[ \rho_c = \frac{3}{8\pi G} H^2 \]
You can see that for larger values of the Hubble constant (faster expansion) \( \rho_c \) takes larger values too. That makes sense, since it would take more mass to produce enough gravitational force to turn around a faster expansion.

CAVEAT: In section 9 we will earn about an “anti-gravity” force due to “dark energy” that can give exceptions this “escape velocity” rule (but the exceptions don’t impact the discussion here).

**Key feature** of the standard big bang cosmology:

The value of \( \frac{\rho_{\text{Universe}}}{\rho_c} \) (also called \( \Omega \)) tends to evolve away from 1, no matter how it starts out.
Omega: $\Omega$ is defined by $\frac{\rho_{\text{Universe}}}{\rho_c} = \Omega$

Flatness: Einstein’s General Relativity teaches us that:

1) When $\rho_{\text{Universe}} > \rho_c$ the universe is “positively curved” or “closed” (travel far enough and you will get back to where you started!)
2) When $\rho_{\text{Universe}} < \rho_c$ the universe is “negatively curved” or “open”
3) When $\rho_{\text{Universe}} = \rho_c$ the universe is “flat”

The punch line: The tendency for the universe to evolve away from $\rho_{\text{Universe}} = \rho_c$ ($\Omega = 1$) plus the fact that $\rho_{\text{Universe}} \approx \rho_c$ ($\Omega \approx 1.02 \pm 0.02$) today mean $\rho_{\text{Universe}} = \rho_c$ to very high accuracy in the past.

For example: At the time when the universe was at the “Grand Unification” temperature ($10^{27}$K, see homework problem 3.1). $\rho_{\text{Universe}} = \rho_c$ had to be true to at least 55 decimal places!

The flatness puzzle: What could have made the universe start in such an unstable state?

8.9.2 Homogeneity Puzzle

Another way the universe has a delicately balanced starting point:

Gravity tends to clump matter together, but the universe starts out very smooth. Gravity will try to form all the matter in the Universe into one giant black hole. Despite having 14 Billion years to do that, the job is *very* far from complete.
NB: In the lecture I discussed the above point without referring to entropy at all. As I discuss in the note below, the entropy approach is not required for this class.

Can quantify using “entropy”: Maximum entropy = total collapse = all matter in one giant black hole!

At time of Grand Unification (T=10^{27}K):

\[
\frac{\text{Entropy of early universe}}{\text{Entropy of giant black hole}} = 10^{-35}
\]

=> Need to carefully chose starting point in “un-collapsed” state.

NOTE: Need not understand entropy, except that we use it here to quantify how un-collapsed the universe is. You will probably not see it used this way again!

8.9.3 Horizon Puzzle

The issue: The starting point of the universe is very special, (homogenous & flat, see above), but if you try and imagine physical processes that could set it up that way, you are up against “causality”.

Causality: No signal (or physical process) can travel faster than the speed of light. Since the time since the big bang is finite many regions in the universe were causally disconnected (as time goes on, the amount of causal contact increases).

Illustration 1: At the time of last scattering, the last scattering surface we see was composed of well over 10^9 causally disconnected regions. Today, most of these are in causal contact, but still “opposite sides” of the last scattering surface have not yet come into contact.

Illustration 2: At time of Grand Unification (T=10^{27}K): The region we observe today was composed of 10^{80} regions that had no contact whatsoever!

Illustration 3: Suppose you meet your roommate for the first time and he/she is wearing the same outfit as you. If you never communicated before that would be slightly surprising, but if you came from different countries that had no trade or other communications that would be really stunning!
8.10 Discussion of the Puzzles

Flatness and Homogeneity puzzles: The universe starts in a strange unstable state (the laws of physics try hard to make the universe not flat, and not homogeneous, yet that is exactly how the universe was at the beginning, to a very high degree).

Horizon puzzle: If you hope to have a physical process explain how the universe got into that unstable starting point, causality seems to say that is impossible.

Note: These are only puzzles if you care about explaining a starting point. The only reason we care about explaining the starting point is that it is so unstable.

Example: Two steel balls (bb’s) stacked on top of one another for 15 billion years cry out for explanation. If they are sitting next to each other, no explanation seems necessary.

Mar 9

Collect HW8 at break

8.11 Cosmic Inflation

The idea: Change the properties of matter at the beginning of the universe so that what we thought was unstable was actually the opposite: That is, make the start of the big bang an “attractor” where many possible starting points are drawn toward the same special state).

The changes one needs to propose seem reasonable in the context of current theories of matter, but they do involve extrapolated current theories beyond the areas where they have been tested.

8.11.1 Tools
Cosmic time $\tau$

*See more complete discussion in homework 9*

- $\tau$: A specially defined time coordinate (let $\tau = 1$ be some very early time in the universe, don’t worry about units)

**Time evolution of normal density**

- matter: $\rho_m = \frac{\rho_m^1}{\tau^3}$
- Useful tool: Think of the curvature of the universe as in terms of
  
  “curvature matter”: $\rho_K = \frac{\rho_K^1}{\tau^2}$ (can have a negative value)

**Density and flatness (normal)**

- The critical density $\rho_c$ turns out to be given by $\rho_C = \rho_{Univ} + \rho_K$
  (also $\rho_c = \frac{3}{8\pi G} H^2$)
- So $\Omega = \frac{\rho_{Univ}}{\rho_C} = \frac{\rho_{Univ}}{\rho_{Univ} + \rho_K}$ and $\Omega \approx 1$ when $\rho_{Univ} >> \rho_K$ => a flat universe has small curvature (of course!)
- Standard big bang: $\rho_{Univ} = \rho_m = \frac{\rho_m^1}{\tau^3}$, which decreases *faster* with time compared with $\rho_K = \frac{\rho_K^1}{\tau^2}$. Namely, as time progresses $\rho_K$ dominates over $\rho_{Univ}$ and the universe becomes less flat (more curved). [Draw plot on board]
- Result: for standard cosmology universe evolves *away* from $\Omega \approx 1$.

**Inflation: Density and flatness (with $\rho_V$)**
• “Potential dominated matter”: \( \rho_V = \frac{\rho_V^1}{\tau^0} = \rho_V^1 \) (no time dependence)

\[ \rho_{Univ} = \rho_m + \rho_V = \frac{\rho_m^1}{\tau^3} + \rho_V^1 \rightarrow \rho_V^1 \]  
This point not covered winter 2010

• As time goes on, \( \rho_{Univ} \approx \rho_V = \rho_V^0 \)  
This point not covered winter 2010

• Winter 2010 version: Simply assume \( \rho_{Univ} = \rho_V \) at some time in the early universe (the period of “cosmic inflation”)

• And \( \rho_C = \rho_{Univ} + \rho_K \rightarrow \rho_{Univ} \): and \( \Omega \rightarrow 1 \) and the universe becomes *more flat* over time!

8.11.2 Using the tools to explain flatness
Suppose that for some period of time in the very early universe, some type of matter took the form of \( \rho_V \).

Suppose at a later time that matter changed form (“decayed into ordinary matter”).

If the above were true, the universe would become dominated by \( \rho_V \) at early times, and be drawn toward \( \Omega \approx 1 \)

Afterwards, the universe would have just ordinary matter, and behave like the “standard big bang” model.

The period when \( \rho_V \) dominates is called the period of “cosmic inflation” (the universe expand exponentially fast) \( d = e^{Ht} \)

Picture:
Result: By postulating a subtle change in the behavior of matter in the early universe, physical processes can *explain* the special tuning of $\rho_1$ close to $\rho_c$ at early times.

8.11.3 Homogeneity and inflation

- During inflation: Exponential expansion takes inhomogeneities from very small scales ($10^{\text{huge number}}$ cm) and blows them up to cosmic scales.
- This offers us a chance to calculate the degree of homogeneity after inflation (because we think we understand the inhomogeneities on very small scales… perhaps not that different from everyday experience).
- It is “straightforward” to construct inflation models that give the right amount of homogeneity after inflation is finished.
• Thus, if you have a good inflation model, you can predict the homogeneity of the universe. (Simple argument that “matter tends to collapse away from homogeneity” does not apply during inflation.)
• No “homogeneity puzzle”
• Condensed version of the above (this is all we covered in Winter 2010): A period of cosmic inflation \( \rho_{\text{Univ}} = \rho_{\text{r}} \) Tends to smooth out inhomogeneities, leaving just very small remaining inhomogeneities that could be the seeds of galaxies and other structure.

8.11.4 Inflation and the horizon puzzle
Bottom line: Cosmic inflation (exponential expansion) dramatically changes the way causality works in the universe. Inflation removes the causality problem.

Pictures: Think about them if they help, ignore them if they do not. (I just expect you to know the “bottom line” stated above).
8.11.5 Building an "inflation model"

Key ingredient: A specific idea of how matter takes on the $\rho_\Lambda$ form, and then switches to an ordinary form later on. Very technical, but certainly possible.

Current status: Lots of ideas, but no single clear winner. Namely, we are confused, as we are about much of physics at ultra-high energies. (Big meeting at UCD in 2003 to discuss inflation) Also a hot topic at COSMO06, also organized by UCD.

- Condensed version of the above (this is all we covered in Winter 2010): A period of cosmic inflation has such different causality properties (due to the exponentially fast expansion rate) that there is no horizon problem.

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<th>Mar 11</th>
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<td>Review Final Exam study info</td>
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8.11.6 Current status of cosmic inflation theory

Model building and observational tests

See Slides (S10)

8.12 Inflation Summary
(This section covered winter 2010)
1. Cosmic inflation is a new (~25 yr old) idea of what happened in the early history of the universe.

2. Cosmic inflation addresses the puzzles discussed in sections 8.9 and 8.10 by
   i) Drawing the universe *toward* a more flat state,
   ii) predicting the (very high) level of homogeneity in the early universe and
   iii) dramatically changing the nature of the cosmic horizon in the early inverse so that the observed universe *is* causally connected even at very early times.

3. Cosmic inflation leads to numerous predictions that can be tested by current and future observations. These include
   i) predictions about features seen in maps of the surface of last scattering (“the microwave sky”),
   ii) the prediction that the universe should be very flat today.
   iii) Predictions of features in the distribution of galaxies today.

4. So far many of the predictions mentioned in item 3) have been tested, and inflation has passed with flying colors.

5. Despite its success, many questions remain about how inflation might have really come about in the early universe. It is a topic of very active current research, and it connected with some of the most interesting outstanding questions in fundamental physics (such as the nature of quantum gravity).

6. The unanswered questions about inflation are sufficiently deep that it could cause inflation to “fail”, but still something is very correct about the predictions it appears to make.

9 Cosmic acceleration.


See supernova movie [Explanation of the video][MPEG movie][Quicktime movie]

Movie 1 http://www.ifa.hawaii.edu/~tully/outreach/movie.html

Continue dark energy slides
“Fate of the Universe”. Tutorial from Astronomy place
Further discussion from Slides

A caveat re: escape velocity: Now we believe there is a strange “dark energy” causing the universe to accelerate. This dark energy contributes positively to $\rho_{\text{Universe}}$ but gives repulsive gravity (pushing things apart).

Dark energy screws up the simple analogy with escape velocity: If $\rho > \rho_c$, the universe can still expand forever, as long as enough of the matter (that makes up the density $\rho$ ) is pushing the universe apart rather than pulling it together. We discussed this as we viewed the “Fate of the Universe” tutorial

NOTE: this caveat does not affect the discussion of inflation, because inflation is about the early universe, and dark energy is only important at very late times in the universe. That is why I did not include this caveat in the discussion there.

10 Concluding Comments