Physics 133 -- Extragalactic Astronomy and Cosmology

• Instructor: Prof. Crystal Martin
  – Lectures: M W 12:30-1:45
  – Office hours: W 2:00-3:00 pm (Broida 2015D)
  – TA: Daichi Hiramatsu (Physics Study Center)

• Textbook:
  – *Introduction to Cosmology*, Barbara S. Ryden, 2nd Edition (required)

• Course covers all 12 chapters in 10 weeks.
• Read Ryden chapters 1-2 (& start 3) this week.
<table>
<thead>
<tr>
<th>Mon/Wed</th>
<th>TOPIC</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2 &amp; 4</td>
<td>[R1-2, 3] Introduction &amp; Observational Foundation</td>
<td>Week 1</td>
</tr>
<tr>
<td>April 9 &amp; 11</td>
<td>[R3-4] Theoretical Foundation</td>
<td>Week 2</td>
</tr>
<tr>
<td>April 16 &amp; 18</td>
<td>[R5] Model Universes</td>
<td>Week 3</td>
</tr>
<tr>
<td>April 23 &amp; 25</td>
<td>[R6] Measuring Cosmological Parameters</td>
<td>Week 4</td>
</tr>
<tr>
<td>April 30 &amp; May 2</td>
<td>[R7] Dark Matter &amp; [R8] Recombination</td>
<td>Week 5</td>
</tr>
<tr>
<td>May 7 &amp; 9</td>
<td>Midterm [R1-6] &amp; [R8] CMB Temperature Fluctuations</td>
<td>Week 6</td>
</tr>
<tr>
<td>May 14 &amp; 16</td>
<td>[R9] Nucleosynthesis &amp; The First Few Minutes</td>
<td>Week 7</td>
</tr>
<tr>
<td>May 21 &amp; 23</td>
<td>[R10] Inflation &amp; The Early Universe</td>
<td>Week 8</td>
</tr>
<tr>
<td>June 4 &amp; 6</td>
<td>[R12] Structure Formation II. Baryons &amp; Photons</td>
<td>Week 10</td>
</tr>
<tr>
<td>Tue June 12</td>
<td>[R1-12] FINAL EXAM: 12-3 pm</td>
<td>Review</td>
</tr>
</tbody>
</table>

**SYLLABUS**

**PHYSICS 133 - Galaxies/Cosmology**

Spring 2018

**OFFICE HOURS**

- **Prof. Crystal Martin**
  - W: 2:00 - 3:00 pm
  - Broida 2015D
  - 893-8760
  - cmartin@ucsb.edu

- **TA: Daichi Hiramatsu**
  - 3 hours
  - Physics Study Center
  - n/a
  - dhiramatsu@ucsb.edu

**LECTURE SCHEDULE**

- MW: 12:30-1:45 Theater-Dance West 2600

**HOMEWORK:** Assignments and Solutions
Physics 133

• Prerequisites: lower division physics series.
• Website: web.physics.ucsb.edu/~phys133/s2018/
• A course syllabus, schedule of lectures, lecture slides, homework assignments, and homework solutions are linked to this website
• Supplementary material is also posted. For example, see link to info on ancient cosmology.
• Hope you enjoy this class. Let me know if I can do anything to make the experience better. You’ll find the material challenging.
• **Homework is due by 1:30 pm Friday.** Use the drop box on the 1st floor of Broida.

• **Grading:**
  – 25% Homework
  – 5% Class participation
  – 20% midterm
  – 50% final exam

**MIDTERM:**
  – Monday May 7th

**FINAL EXAM:** June 12\textsuperscript{th}, 2018 – 12:00-3:00pm

  – Advise me of any conflicts with these dates this week!
Cosmology is the study of the universe as a whole
Cosmology Addresses Questions Fundamental to the Human Condition

• What is the universe made of?
• How big is the universe?
• Is the universe evolving?
• Did it have a beginning?
• If so, how old is the universe?
• Where will it end up?
• Is there an end to the universe?
Cosmology is Based on Observations

- When data are lacking, we may use aesthetic or philosophical reasons to motivate a model.
- Copernicus explained retrograde motion with a new model that was simpler than the epicycles used by the Greeks.
The role of observations

• Experiments and Observations force us to modify/change our view of the Universe. Examples:
  – Galileo’s observations of sun spots proved that the heavens are not time-invariant
  – Galileo’s observations of the phases of Venus proved the earth and venus orbit the sun.
  – Hubble’s measurement of galaxy redshifts showed that the Universe is not static
  – High speed motions of stars in galaxies show that either we do not understand gravity or that there is a large amount of “dark matter”, i.e. different stuff that the ones that makes you and me (and Earth)
Interplay of Cosmology and Physics

- Cosmology uses all the knowledge of physics that we learn from laboratory experiments
- Some of the most extraordinary discoveries in physics come from cosmology: dark matter and dark energy, just to name two
Tools of the trade – Telescopes as time machines
Your lifetime could be a golden era for cosmology.
Cosmological Models

• The model must reproduce observations and make falsifiable predictions.
• Can we put together a physical model of the universe and its contents?
• The best we could come up so far is the so-called Standard Cosmological Model (by analogy with particle physics’ Standard Model), the Benchmark Model, or the Concordance Model
A fundamental dilemma…

• We only have one Universe! We cannot replicate/alter/reproduce our sample.

• Experiments and Observations can only be made from one specific point in space and time -- Earth now.

• Yet we would like to construct a scientific theory that describes the universe everywhere and at all times.
The solution is called the cosmological principle

- Physicists postulate a universal principle: our location in the universe is not special.
- This postulate is deeply rooted in two fundamental principles of physics:
  - The laws of physics (whatever they are!) do not depend on space and time
  - Physical explanations of natural phenomena should be as simple as possible (Ockham’s razor)
Cosmological Principle:

- The universe is homogeneous and isotropic.
  - Similar to the Copernican Principle: there’s no special place in the universe

- Applies on scales > 100 Mpc
- Does homogeneity imply isotropy?
- Does isotropy imply homogeneity?
Homogeneous but not Isotropic

Isotropic (about a point) but not Homogeneous

Isotropy at all points in space implies homogeneity
Isotropy and Homogeneity of the Universe: Map Making

• Mapping a sphere onto a plane -- Hammer-Aitoff projection preserves area
Isotropy and Homogeneity of the Universe: Map Making
Isotropy and homogeneity: Galaxies

The Near-Infrared Local Universe

Celestial Equator (Geo-centric)

Galactic Plane toward Anti-center

As seen in the 2MASS Near-Infrared survey:
J (1.2 μm), H (1.6 μm) and Ks (2.2 μm).
The All Sky image is composed of sources with integrated fluxes brighter than Ks = 18.0 magnitude, comprising the 2MASS Extended Source Catalog (XSC) – more than 1.9 million galaxies, and the Point Source Catalog (PSC) – nearly 3.5 million Milky Way stars [here tinted blue to show contrast with the background galaxies].
The map is projected with an equal area projection in the Geo-equatorial system (centered at the Right Ascension). The plane of the Milky Way runs diagonally across the image, with the Galactic anti-center facing you.

The image was created by Thomas Jarrett & Robert Hurt (IPAC-Caltech).
Numerical Model of Structure

100 Mpc
Isotropy and homogeneity of the Universe

- If we look far enough (100Mpc) the universe is isotropic (i.e. invariant under rotation)
- This is illustrated beautifully by the cosmic microwave background… (we’ll come back to this in the next class)
- What does the dipole mean in terms of reference frame?
Perfect cosmological principle

Perfect (or strong) cosmological principle: The universe is homogenous, isotropic, and **time-invariant**

Inconsistent with observations!
Key Point: Isotropy and homogeneity of the Universe.

• One of the basic assumption of cosmology is that we are observers in a random place. We are not in a special place in any way (Copernican Principle)
• Therefore we CANNOT be at the center of the universe. Thus if the universe is invariant under rotation around a random point it must also be invariant under translation: homogenous.
• **ONLY ON LARGE SCALES. OF COURSE ON SMALL SCALES IT IS NOT!!!**
Olbers’ paradox.
The night sky is dark!

• This apparently superficial statement has very profound consequences.
• This observational result is evidence in favor of the big bang
Olbers’ paradox. A step back..

- Copernican system requires the stars to be much further away than the sun; otherwise their parallax would be detected with the naked eye.
- Newton’s model of the universe was:
  - Eternal
  - Infinite (otherwise it would collapse gravitationally)
  - Flat Space
  - Time independent
- So surface brightness is independent of distance.
Olbers’ s paradox. What does the sky look like in Newton’ s model?

- For every line of sight sooner or later you find a star
- This would mean that the sky should have the same surface brightness of the sun, your average Joe star, e.g. the Sun...
- Assumptions: starlight is not attenuated, nL is constant in space and time, the universe is infinitely large, and the universe is infinitely old
Olbers’ paradox.
Olbers’ solution.

- Olbers postulated that the Universe was filled with an absorbing medium, like fog.
- However, if light is absorbed it would heat up the medium, which would re-radiate, producing light albeit at different wavelengths, so this doesn’t work!
Olbers’ paradox.
The Big-Bang’s solution

• In the Big Bang model the Universe is finite in TIME (13.7 billion years)
• This means that we can only see as far away as light has had time to travel
• Furthermore stars were not always shining (the sun for example is 4.5 Gyrs old).
• More later..
Olbers’ paradox. Summary

- The night sky is dark
- This implies that the emission of starlight in the universe must be finite, in space, time or both.
- This is fundamental test for any cosmological model
- The Big-bang explains Olbers’ paradox with the finiteness of the lifetime of the Universe and hence of its stars:
- The universe is NOT eternal in the past! The universe evolves!
Expansion of the Universe. Empirical facts.

• In the early XX century, Hubble and Humason found out that the spectra of most galaxies are redshifted (the WAVELENGTH $\lambda_0$ of some spectral feature is moved to a longer wavelength $\lambda$)

• The redshift $z$ is the amount of shift towards longer wavelengths: $z = (\lambda - \lambda_0) / \lambda_0$ or $1 + z = \lambda / \lambda_0$

• For $z$ much smaller than 1, say $z < 0.1$, the redshift can be expressed as a velocity $v \sim cz$, by analogy with the Doppler effect.
Measuring Redshifts
Spectral Templates (e.g. Kennicutt 1992)
Measuring Redshifts
Spectral Templates (e.g. Kennicutt 1992)
Measuring Redshifts, an example.

CaK 3933 Å

Where is the feature now?

\[ Z=0 \]

- \( Z=? \)
- \( V=? \)
Measuring redshifts, an example.

CaK 3933 Å

Where is the feature now?

Z=0

• Z=0.1
• V=30,000 km/s
Hubble’s law: galaxies are “moving away” from us!

- Hubble found that redshift (or velocity) is proportional to distance (Hubble’s law): if you measure double speed, you also measure double distance!
Hubble’s law: the Hubble constant

- The ratio between velocity $v$ and distance $d$ is a constant, called the Hubble Constant or $H_0 = \frac{zc}{d} = \frac{v}{c}$, measured in km/s/Mpc
- This is phenomenal! If we know $H_0$ it is sufficient to measure velocity (or redshift), which is easy, as we saw earlier, to find out the distance to any galaxy!!
Even Hubble makes mistakes....

- Hubble’s first measurement of the Hubble constant was wrong: 500 km/s/Mpc, instead of the current best estimate of 70 km/s/Mpc
Even Hubble makes mistakes….

- Hubble’s mistake was due to various reasons including that he used as standard candles things that were not standard candles.
However Hubble’s law is valid.. and we can use it to infer distances.

• Astronomers prefer to use redshift instead of velocity because this is what we measure.

• Also redshifts are not properly a measure of speed in the common sense of the world, but a measure of the expansion of the Universe as we will see.

• For any measured galaxy redshift, Hubble’s law gives you the distance to the galaxy, provided the expansion rate of the Universe is large compared to peculiar velocities.
Hubble’s Law. Discussion

• Are all galaxies redshifted?
• No
• Why?
The Universe is expanding

- Hubble’s law is not only a convenient way to obtain distances to galaxies from their redshifts.
- Hubble’s law has a much more profound significance.
- In the current standard cosmological model, Hubble’s law is believed to be the result of the expansion of the Universe.
- Expansion in an isotropic model = Hubble’s law [Blackboard]
The Universe is expanding
Meaning of the Hubble constant

- In the standard model the Hubble constant represents the current expansion rate of the Universe.
- In “normal” units the Hubble Constant is 1/14 Gyrs.
- If the expansion rate were constant, the Universe would be of finite age, 14 Gyrs since the Big Bang.
- The horizon distance is the distance a photon travels in the finite age of the universe.
- This solves Olbers’ paradox. The size of the visible universe is limited to $r_H \sim c \left(1/H_0\right)$. [Blackboard]
- The large value of the Hubble constant obtained by Hubble implied a much shorter life of the Universe, of order 1-2 Gyrs. This caused problems as it was inconsistent with the age of the Earth (4.5 Gyrs), for example.
Is there an age problem? How old are the oldest stars?

- The age of stars can be inferred from stellar evolution models, by analyzing the luminosity and temperatures of stars.
- Globular clusters are made of very old stars, all in the same location.
Is there an age problem? How old are the oldest stars?

Age of the oldest globular clusters
Ok with the current estimate 13.7 Gyrs.
Not with Universes without dark energy!
J0815+4729 – Example of a very old star

It is extremely iron poor.
Is there an age problem? How old are the oldest galaxies?

- The age of galaxies can be inferred from stellar evolution models, by analyzing their integrated spectra.
- Elliptical galaxies are made of very old stars, up to 12 Gyrs or so.
Is there an age problem? How about at high redshift?

- Applying the same technique people have measured the ages of the oldest galaxies as a function of redshift.
- There is a clear upper envelope close to the maximum age of the Universe at that redshift.

Jimenez et al. 2005
Is there an age problem?

- No
- Quite the opposite, the age of the oldest stars in the Universe are remarkably consistent with the age of the universe itself, at any redshift where we can measure it.
- This does not prove that the model is right, but is a great triumph of the theories of the big bang and that of stellar evolution.
The universe is expanding.
Frequently asked questions...

• What is the universe expanding into?

• Nothing, the universe is all there is, spacetime is expanding

• Where is the center of the expansion?

• Nowhere, there is no center, the universe is homogenous and isotropic

• Do we expand as well?

• No, because we are bound by electromagnetic forces

• Do galaxies expand?

• No because they are bound by gravity and they detach from the Hubble Flow
Cosmic Microwave Background. Anisotropies from WMAP

The CMB sky, circa 2002…
Cosmic Microwave Background

- The cosmic microwave background was discovered as a background “noise” a real problem for telecommunication satellites (1965)
- Wherever Penzias and Wilson pointed their antenna they would detect a microwave signal, very uniform across the sky
- This signal is now called the cosmic microwave background...
Cosmic Microwave Background

- The CMB was already visible in the data taken by Dunham and Adams of the properties of CN in the interstellar medium …back in 1937
- The saw that CN was excited as if it was immersed in a thermal bath of radiation of temperature T~3K…
- But nobody realized it.. So the Nobel Prize went to Penzias & Wilson… and not to Dunham and Adams.. Such is life..
Cosmic Microwave Background

- A group of physicists (initially Gamow (1948) and then Alpher and Hermann (1950) and then Dicke and his group at Princeton) had predicted such radiation, from the so-called big bang nucleosynthesis theory (later in the class...)
- The CMB was predicted to be:
  - Thermal
  - At a temperature of about 5K
  - Isotropic

Dicke was devising a CMB search when the discovery was made. His paper with Peebles, Roll, and Wilkinson presented the cosmological interpretation alongside the Penzias and Wilson paper.
Cosmic Microwave Background

- Discovery of CMB settled debate between Steady-State and Big Band models.
- Why?
  - CMB photons are a relic of the epoch when matter and radiation were in equilibrium, i.e. interacted frequently.
  - And the background radiation was much hotter then. Hot enough to ionize hydrogen and create free electrons.
Cosmic Microwave Background. Thermal “Blackbody” Radiation

- We know Penzias and Wilson detected isotropic radiation, so that was consistent with the Big Bang model and the Cosmological Principle
- The theory predicted it to be thermal, i.e. a blackbody.

Plank’s Equation

\[
B_\lambda = \frac{2\hbar \omega^2}{\lambda^5} \frac{1}{\exp \frac{\hbar \omega}{\lambda kT} - 1}
\]

Where:
- \(B_\lambda\) = Magnitude of Radiation per Wavelength.
- \(\lambda\) = Wavelength.
- \(h\) = Plank’s Constant (6.6238 * 10^{-34} J/\text{s}).
- \(c\) = Speed of Light (3.0 * 10^8 m/s).
- \(k\) = Boltzmann Constant (1.3807 * 10^{-23} J/K).
Properties of Blackbody Radiation

1. Matter and radiation in equilibrium produces a characteristic spectral shape

2. Radiative emissivity
   \[ F = \sigma T^4, \] where
   \( \sigma = 5.67 \times 10^{-8} \text{ J/s/m}^2/\text{K}^4 \)

3. Wien’s Law - hotter body produces higher energy photons;
   \( \lambda_{\text{max}} T = 0.3 \text{ cm } \times \text{ deg} \)

4. Energy density -
   \[ \varepsilon = a_{\text{rad}} T^4, \] where
   \( a_{\text{rad}} = 7.56 \times 10^{-16} \text{ J/m}^3/\text{K}^4 \)

But is the CMB radiation really a perfect blackbody spectrum?
Is the Microwave Background Radiation Thermal?
COBE got the answer
Cosmic Microwave Background. The CMB is a “perfect” Blackbody
CMB properties

- CMB T = 2.725 K today.
- A hot, dense universe provides an environment where matter and radiation are in Thermodynamic Equilibrium.
- Universe becomes transparent at T < 3000 K.
- The photon gas cooled due to the expansion of the universe.
  - Expansion is adiabatic
  - Scaling of T with scale factor (or redshift)
  - Expansion preserves blackbody
  - CMB photons are a relic of the epoch when matter and radiation were in equilibrium, i.e. interacted frequently. And the background radiation was much hotter then. Hot enough to ionize hydrogen and create free electrons.
What is the universe made of? “normal” matter

- Ordinary matter is made for the most part of protons and neutrons, i.e. quarks up and down.
- For this reason we refer to ordinary matter as baryonic matter (the electrons contribute only a small fraction of the mass)
- Neutrinos should not have mass in the standard model, but they do (neutrino oscillations) [See HW problem 4]
- No antimatter is observed!

- The sun is made of:
  - Hydrogen (74% by mass)
  - Heavier elements (1%) commonly referred to as “metals” by astrophysicists
  - Helium (25%)
- This is way more He than expected from a universe initially made of Hydrogen where Helium is produced in stars…
- This is a common problem: Helium abundance is always ~25%
Helium abundance. The Big Bang solution

• He is produced in the early Universe when $T$ was high enough (above $\sim 10^9$ K) to allow for nuclear fusion. Recall $T(t) = T_0 a_0 / a(t)$, so the scale factor was $\sim 3e5$ times smaller during the epoch of nucleosynthesis than at the surface of last scattering.

• Why do you need high temperature to do fusion?

• We will see later on that the Big Bang theory predicts exactly the abundance of all heavy elements. Note: this is the third pillar of the Big Bang theory (+ Hubble Expansion + CMB)
End Week 1

• HW #1 due at 1:30 pm Friday; please use dropbox in Broida lobby
• Office Hours today
• Read [R] ch. 3.
• See you on Monday!
Week 1: Review

1. Cosmological models use the same physical laws that we study in the laboratory and are both motivated and tested by observations.

2. Copernican, or Cosmological, Principle.
   - The Universe is the same throughout.
   - **ONLY ON LARGE SCALES ≥ 100 MPC. ON SMALL SCALES IT IS NOT!!!**
   - Observations of CMB and galaxy surveys are the same in every direction (isotropic). Since there is no special place, it is the same in every direction from every point, and therefore homogeneous.

3. The Universe is not time invariant. Only the weak form of the cosmological principle applies.
Week 1: Review

• Empirical foundations of the Big Bang theory. I:
  – The night sky is dark.
    • Inconsistent with an eternal, static and infinite Universe
  – The spectra of distant galaxies appear “redshifted” as if the distance between us and them was increasing with time.
    • In the Big Bang theory this is interpreted as due to the expansion of the Universe.
  – The ages of stars (and galaxies) are found to be less than $1/H_0$, consistent with the finite lifetime of the universe.
Week 1: Review

• Empirical foundations of the Big Bang theory. II:
  – The Universe is filled with an almost perfectly isotropic blackbody radiation at a temperature of 2.7 K. This is interpreted in the Big Bang theory as the remnant of an hot state when radiation and matter were in thermal equilibrium.
  • [Note: You should be able to derive the scaling of the temperature of BB radiation with scale factor or redshift.]
  – The baryonic matter in the universe is found to have a very regular chemical composition, mostly H, He and tiny amounts of heavier matter. Stars cannot produce all the He. Hence the universe must have been hot enough and dense enough for nucleosynthesis to occur before the first stars formed.
Units in astronomy. Length:

- Astronomical Unit (AU) = average distance Sun – Earth. \( \sim 1.5 \times 10^{11} \text{ m} \) or \( 1.5 \times 10^{13} \text{ cm} \). Too small for our purposes.
- parsec (pc) -> kiloparsec (kpc), megaparsec Mpc (Mpc), Gigaparsec (Gpc)
  - \( 1 \text{ pc} = \) Distance at which 1 Astronomical Unit subtends an angle of 1 arcsecond \( (3.086 \times 10^{16} \text{ m} \) or \( 3.086 \times 10^{18} \text{ cm} \)
- Examples:
  - Distance between stars in the solar neighborhood: pc
  - Size of a galaxy like the Milky Way: kpc
  - Distance between galaxies or size of clusters: Mpc
  - Distance of the most distant objects known: Gpc
Units in astronomy. Mass, Luminosity and Time:

• M. Solar mass: 1.98e30 kg or 1.98e33 g
  – A large galaxy is typically $10^{11-12}$ solar masses
  – A cluster is typically $10^{14-15}$ solar masses

• L. Solar luminosity: 3.8e26 watt or 3.8e33 erg/s
  – A large galaxy is typically $10^{10-11}$ solar luminosities (what does this mean in terms of mass to light ratio?)

• T. Period of Earth’s orbit (yr): $\sim3.15 \times 10^7$ s
  – Typically times are measured in Gyr. The age of the Earth is 4.6 Gyr, the age of the Universe is 13.7 Gyr.
Units in astronomy. Units from microscopic physics

- E. Energy: eV = 1.6e-19 J or 1.5e-12 ergs
  - Mass of the electron = 0.511 MeV
  - Mass of the proton = 938 MeV
- λ. Angstrom: Å = 1e-10 m or 1e-8 cm
- Planck units (combining fundamental constants):
  - \( l_p = \sqrt{\frac{G \hbar c^3}{c^3}} = 1.6e-35 \text{ m} = 1.6e-33 \text{ cm} \)
  - \( M_p = \sqrt{\frac{\hbar c}{G}} = 2.2e-8 \text{ kg} = 2.2e-5 \text{ g} \)
  - \( t_p = \sqrt{\frac{G \hbar}{c^5}} = 5.4e-44 \text{ s} \)
  - Planck energy (\( E_p = m_p c^2 \)) and temperature (\( E_p = k T_p \))
  - \( E_p = 1.2e28 \text{ eV} \)
  - \( T_p = 1.4e32 \text{ K} \)