Ast 243: Cosmological Physics

Course text book: Ryden, Introduction to Cosmology, 2nd edition

- Olber’s paradox, expansion of the universe: Ch 2
- Cosmic geometry, expansion rate, acceleration: Ch 3, 6
- Cosmic dynamics and composition: Ch 4, 5
- Dark matter and dark energy: Ch 5, 7
- Hot big bang and origin of species: Ch 9
- Inflation: Ch 10
- Cosmic microwave background: Ch 8
- Gravitational instability and structure formation: Ch 11, 12

Final (30%), format TBD

HW (70% TA Dimitrios Tanoglidis, dtanoglidis@uchicago.edu)
Set 1:

Expansion of the Universe
Observables

• Most cosmological inferences are based on interpreting the radiation we receive on Earth from astrophysical objects: stars, galaxies, clusters of galaxies, cosmic microwave background...

• Largely electromagnetic radiation but now also neutrinos, cosmic rays, and most recently, gravitational waves

• For light coming from a single object, e.g. a star or galaxy, let’s think about the basic observable of the radiation that we measure in a detector
  flux: energy received by the detector per unit time per unit detector area

• How do we convert this basic observable into a 3D model?
Galaxy: Optical Image

- Place nearby stars on a map of the sky and measure their flux
- Color overlay, furthest source: microwave background
• Energy flux $F$ given a luminosity $L$ of the source $L = \Delta E / \Delta t$ (energy/time)

$$F = \frac{\Delta E}{\Delta t \Delta A} = \frac{L}{4\pi r^2}$$

• Astro units: often in cgs erg s$^{-1}$ cm$^{-2}$ (mks W m$^{-2}$)

• Energy conservation says rate of energy passing through the shell at $r_1$ must be the same as $r_2$

• Thus flux decreases as $1/r^2$ from the source

$$F(r_1)4\pi r_1^2 = F(r_2)4\pi r_2^2$$

$$F \propto r^{-2}$$
From 2D to 3D

- So even without knowing the luminosity of a set of standard objects, we can judge relative distance from flux
  \[ \frac{r_2}{r_1} = \left( \frac{F_1}{F_2} \right)^{1/2} \]

- This is the idea of a standard candle, star of the same type, supernovae etc.

- Aside: certain variable stars called Cepheids are excellent standard candles – pulsation period is linked to the luminosity so we can pick out objects of the same luminosity and use the measured flux to put place their relative position on a map.

- 2D map becomes a 3D map and we can start to talk about the physical structure of the universe.

- We can calibrate the absolute distance to the nearby ones by other methods, ultimately parallax - change in angle on the sky as earth orbits the sun at 1AU indicating distance as \( d\alpha = \pm (1\text{AU}/d) \).
Cosmological Units

- Astro and cosmo units often look bizarre at first sight - however they are useful in that they tell you something about the observation behind the inference.

- Cosmologists' favorite unit is the megaparsec:

  \[ 1 \text{Mpc} = 3.0856 \times 10^{24} \text{cm} \]

  because it is the typical separation between galaxies.

- In other astrophysical contexts, use length scales appropriate to the system - Mpc is based on the AU - earth-sun distance:
  - 1 AU subtends 1 arcsec at 1 pc – parallax to close objects allows us to convert relative distance to absolute distance
  - 1 pc: nearest stars, 1 kpc distances in the galaxy, 1 Mpc distance between galaxies, 1 Gpc distances across observable universe
Received Light: Received History

- Because of the finite light travel time, light from distant objects is emitted at earlier times so sky maps become snapshots of the history of the universe

\[ \Delta t = \frac{\Delta x}{c} \]

- Speed of light can be thought of as a conversion factor between time and distance (see problem set)

- In this class we will often measure time and space in the same units, i.e. we set \( c = 1 \) and measure time in Mpc or distance in (light) years

- We shall see that the earliest light we can measure (from the most distant sources) comes from the cosmic microwave background, the afterglow of the big bang - many Gpc or Gyr away
Observables: Surface Brightness

- If the 2D map resolves the object in question, we can do better: measure surface brightness

- Direction: colimate in an acceptance angle \(d\Omega\) normal to \(dA\) → surface brightness

\[
S(\Omega) = \frac{\Delta E}{\Delta t \Delta A \Delta \Omega}
\]

- Units: for example in cgs, \(\text{erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}\) or mks, \(\text{W m}^{-2} \text{ sr}^{-1}\)
Surface Brightness Conservation

- Surface brightness $\Delta \Omega = (\lambda/d)^2$ for a region with fixed size $\lambda$

$$S = \frac{F}{\Delta \Omega} = \frac{L}{4\pi d^2} \frac{d^2}{\lambda^2}$$

- In a non-expanding geometry, these two distances cancel

$$S = \text{const.}$$

- Aside: since $S = L/4\pi \lambda^2$, astro/cosmo units for galactic scale objects are also often quoted in $L_\odot/\text{pc}^2$
Olber’s Paradox

- Surface brightness of an object is independent of its distance
- So since each site line in universe full of stars will eventually end on surface of star
- Olber’s Paradox: why isn’t night sky as bright as sun (not infinite)
- We shall see that the resolution lies in the expansion of the universe:
  - finite “horizon” distance for the observable universe
  - and that the two distance factors don’t cancel

- To understand the expansion, we need not just a map of the universe but a measurement of motion
Observables: Redshift

- We can also measure the frequency of radiation from objects

- If emission contains atomic lines with a natural rest frequency $\nu_{\text{rest}}$ we can measure the redshift or velocity by the ratio of observed to rest frequency

$$1 + z = \frac{\nu_{\text{rest}}}{\nu_{\text{obs}}} = \frac{1 + \frac{v}{c}}{\sqrt{1 - \frac{v^2}{c^2}}}$$

and for $v \ll c$, $z = \frac{v}{c}$

- Here $v$ is the recession velocity - i.e. light is shifted to the red if the object is receding from us

- In this class we’ll often use units where $c = \hbar = 1$ which means time and length are energy are measured in the same units

- If units don’t make sense add $c, \hbar$ until they do (see problem set)!
Expansion of the Universe

• Now let’s put together these observational tools

• Given a standard candle with known luminosity $L$, we measure its distance $d$ away from us from the measured flux $F = L / 4\pi d^2$

• Given atomic line transitions, we measure the redshift $z$ or equivalently the recession velocity $v$

• Hubble then plotted out recession velocity as a function of distance....
Hubble Law

- Hubble in 1929 used the Cepheid period luminosity relation to infer distances to nearby galaxies thereby discovering the expansion of the universe.

- Hubble actually inferred too large a Hubble constant of $H_0 \sim 500\text{km/s/Mpc}$ due to a miscalibration of the Cepheid distance scale.

- $H_0$ now measured as $74.03 \pm 1.42\text{km/s/Mpc}$ by combining a suite of distance measurements [arXiv:1903.07603]
Fundamental Properties

- Hubble law: objects are receding from us at a velocity that is proportional to their distance
- Universe is highly isotropic at sufficiently large distances
- Universe is homogeneous on large scales
- Let’s see why the first property, along with the implications of the second two that we are not in a special position, imply the universe is expanding

- The Hubble law sounds much like we are at the center of an explosion outwards but that would violate homogeneity and put us in a special place
- To be consistent with both, we posit space itself is expanding...
Expansion of the Universe

- Consider a 1 dimensional expansion traced out by galaxies

\[ \frac{\Delta x}{\Delta t} = H_0 d \]

- From the perspective of the central galaxy the others are receding with a velocity proportional to distance

- Proportionality constant is called the *Hubble Constant* \( H_0 \)

- Each observer in the expansion will see the same relative recession of galaxies
Expansion of the Universe

- Generalizes to a three dimensional expansion. Consider the observer at the origin and two galaxies at position \( d_A \) and \( d_B \)

- Recession velocities according to the observer

\[
    v_A = H_0 d_A, \quad v_B = H_0 d_B
\]

- According to galaxy \( B \), the recession velocity of galaxy \( A \) is

\[
    v_B - v_A = H_0 d_B - H_0 d_A = H_0 d_{AB}
\]

so that \( B \) will see the same expansion rate as the observer at the origin given the linearity of Hubble’s law

- Hubble’s law is best thought of as an expansion of space itself, with galaxies carried along the “Hubble flow”
Olber’s Paradox Redux

• In an expanding universe Olber’s paradox is resolved

• First piece: age finite so there is a finite distance light can travel called the horizon distance - even if stars exist in the early universe, not all site lines end on stars

• But even as age goes to infinity and the number of site lines goes to 100%, surface brightness of distant objects (of fixed physical size) goes to zero
  – Angular size increases
  – Redshift of energy and arrival time

we’ll see in the next set of lectures

\[ S \propto (1 + z)^{-4} \]
Supernovae as Standard Candles

- Type 1A supernovae are white dwarfs that reach Chandrashekar mass where electron degeneracy pressure can no longer support the star, hence a very regular explosion.

- Moreover, the scatter in luminosity (absolute magnitude) is correlated with the shape of the light curve - the rate of decline from peak light, empirical “Phillips relation”.

- Higher $^{56}N$, brighter SN, higher opacity, longer light curve duration.
Beyond Hubble’s Law

- Type 1A are therefore “standardizable” candles leading to a very low scatter $\delta m \sim 0.15$ and visible out to high redshift $z \sim 1$

- Two groups in 1999 found that SN more distant at a given redshift than expected

- Cosmic acceleration discovery won the 2011 Nobel Prize in Physics

- Requires more on cosmic geometry to understand...