Astro 507
Lecture 3
Jan 27, 2014

Announcements:

- Preflight 1 due Friday at 9am `www: assignment`
  Note: answer in *two parts*
  1. reading response: private, only I see
  2. open-ended discussion question: public, everyone sees

Last time: cosmologist's toolbox of observables
`www: Galactic coordinates`
Q: we're doing cosmo–why even use Galactic coords?
zeroth-order large-scale structure *Q: namely?*

Today: Observational/Conceptual Foundations of Cosmology
⋆ Cosmological Principle
⋆ Observed Cosmic Kinematics: Hubble's Law
⋆ Implications of Cosmo Principle + Hubble Law

Observational Cosmology: Zeroth-Order Picture

Cosmic Matter Distribution

observable cosmo "building blocks" – galaxies
$\approx$ all stars in galaxies

on *large scales* ($\gg$ 10 Mpc) properties same everywhere
U is homogeneous
on *small scales* ($\lesssim$ 10 Mpc) clumps, voids
highly inhomogeneous

more quantitatively: smooth/"coarse-grain" U at different scales
find rms mass or density fluctuation in sphere of radius R

- clearly, $\delta M/M \gg 1$ over typical gal separation $R \sim 1$ Mpc
- but $\delta M/M \sim 1$ at $R \sim 10$ Mpc
- $\delta M/M < 10^{-4}$ at $R \sim 1000$ Mpc
$\Rightarrow \delta M/M \rightarrow 0$ for large R

Now scan around the sky

directional dependence:
on large scales, galaxy distribution looks
(statistically) same in all directions
$\rightarrow$ on large angular scales, **U is isotropic**

The Universe to Zeroth Order: Cosmological Principle

Observations teach us that
• at any instant of cosmic time ("epoch")
• to "*zeroth order*":
the Universe is both

1. **homogeneous** *average properties same at all points*
e.g., mass density anywhere is same as mass density everywhere!
i.e., $\rho(\vec{r}) = \rho$ indep of $\vec{r}$!

2 **isotropic** *looks same in all directions*

"Cosmological Principle"
the universe is homogeneous & isotropic
first guessed(!) by A. Einstein (1917)
• no special points! no center, no edge!
• "principle of mediocrity"? "ultimate democracy?"

Q: do you need both?
Q: e.g., how can you be isotropic but not homogeneous?
Q: e.g., how can you be homogeneous but not isotropic?

Example: Cosmo principle and galaxy properties

Q: if cosmo principle true, how should it be reflected in observations of galaxies at any given time?

Q: what does cosmo principle say about how galaxy properties evolve with time?

Cosmo Principle and Galaxy Properties

at any instant of time:

- **average** density of galaxies same everywhere

- *distribution* of galaxy *properties* same everywhere
  range of types
  range of colors
  range of L, M, ...
  ratios of normal/dark matter

Note that these are very restrictive constraints!

time evolution of galaxies:

- must maintain large-scale homogeneity and isotropy
- but otherwise, *by itself cosmo principle allows any changes!*

Cosmo Principle hugely powerful & the "cosmologist's friend"
very strongly constrains possible cosmologies
$\rightarrow$ large-scale spatial behavior maximally simple

Cosmic Kinematics

Slipher, Hubble 1920's: galaxies' spectral lines shifted:

- galaxies move wrt us!
- all* galaxies show shift to red:

$\lambda_{\rm obs} > \lambda_{\rm lab} = \lambda_{\rm rest}$

Define: **redshift** z

$$z = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}} \tag{1}$$

if interpret as Doppler (for non-relativistic $v \ll c$)

$$v \approx cz$$

*Sloan Survey: $\sim 800,000$ spectroscopic galaxy redshifts

16 galaxy blueshifts (many spurious), all $|z| \lesssim 0.001 \rightarrow$ Local Group (bound structure)

a big ASTR596PC thanx to data miner Adam Myers

Bizarre/Elegant Relativity/Particle Units I

chic relativity/particle physics parlance:
all v implicitly *in units of* c

amounts to

$$v_{\text{chic}} = \frac{v_{\text{ordinary}}}{c} \tag{2}$$

equivalent to putting $\boxed{c = 1}$
with rule: insert c factor anytime need v units

example: chic first-order Doppler relation
"$v \approx z$"

Distance–Speed Correlation

Edwin Hubble (1929)

`www: Hubble PNAS paper`

`www: original, old-school Hubble diagram`

groundbreaking despite challenges:

- data available only for nearby galaxies
- lots of scatter
- distance measures later found to be systematically wrong by huge factor

speed-distance correlation: linear

$$v_r \propto r \tag{3}$$

Hubble: $v_r = Kr$

but isotropy implies *Q: what?*

Hubble's Law

Hubble: $v_r = Kr$
isotropy $\Rightarrow$ same K in all directions
modern: Hubble's Law

$$\boxed{\vec{v} = H\vec{r}} \tag{4}$$

at present: time t_0 ("sub-0 = today")
measure: *Hubble* Key project (Cephieds)

$$H_0 = 73 \pm 3_{\text{stat}} \pm 7_{\text{sys}} \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{5}$$

Hubble parameter or Hubble "constant" *Q: why scare quotes?*
Q: what are dimensions of H?
Q: why these crazy units?

The Plague of "Little h"

Back in the old days ($\gtrsim$ 10 yr ago): H_0 poorly measured

$H_0(\text{old data}) \sim 50 - 100\ \text{km s}^{-1}\,\text{Mpc}^{-1}$

Worse still: many cosmo results sensitive to H_0

$\rightarrow$ how to show effect of uncertainties?

Parameterized Uncertainty:

introduce "little h" via

$$H_0 \equiv 100\ h\ \ \text{km s}^{-1}\ \text{Mpc}^{-1} \tag{6}$$

i.e., $h = H_0/100\ \text{km s}^{-1}\,\text{Mpc}^{-1}$; (sometimes also called h_{100})

- back in the day, could only say: $h = 0.5 - 1$
- now–*HST* Cephieds: $h = 0.73 \pm 0.03 \pm 0.07$
  Planck CMB lensing $h = 0.673 \pm 0.012$

Q: little h is ugly–why invent it? why is it useful?

Why Little h?

can always write today's Hubble parameter as

$$H_0 \equiv 100 \; h \;\; \text{km s}^{-1} \text{ Mpc}^{-1} \tag{7}$$

Why useful?

we will see: H_0 enters in most cosmological measurements

- uncertainty in H_0 propagates to many other quantities
- convenient to see how H_0 affects each quantity

example: what is distance to a $z = 0.1$ galaxy?

use Hubble law

$$d(z = 0.1) \approx \frac{cz}{H_0} = 300 \; h^{-1} \text{ Mpc} \tag{8}$$

Today H_0 nightmare mostly over, but fossil h haunts us still

$\rightarrow$ whenever you see it, think roughly $h \approx 0.7 \approx 1/\sqrt{2}$

Structure + Dynamics: Evolution

observe:

- U. homogeneous, isotropic
- Hubble law $\vec{v} = H\vec{r}$

  Q: restate in simple language? Not a trick question...

  `www: artist's conception`

Q: how reconcile?

at least 2 logical possibilities...

1. "Egoist" interpretation: we are at the center of U.

imagine an explosion at $t = 0$
and let galaxies all start at $r = 0$
and fly away at with distribution of const speeds v_{gal}
but we remain at $r = 0$ until now: t_{today}

Q: what distribution of galaxy distances r_{gal} *would we see today?*

Q: does this model predict a velocity–distance correlation?
if not, why? if so, what? comparison with data?

Q: what is the age of the Universe in this model?

in "explosion" model:

each galaxy coasts at initial (constant) velocity

and after time $\Delta t = t_{\rm today}$:

- $\vec{r}_{\rm gal} = \vec{v}_{\rm gal} t_{\rm today}$ fastest $\rightarrow$ farthest!
- so $\vec{v}_{\rm gal} = \vec{r}_{\rm gal}/t_{\rm today} \equiv H_0 \vec{r}_{\rm gal} \propto \vec{r}_{\rm gal}$: recover Hubble's law!
- can calculate age of Universe as

  $t_{\rm today} = v_{\rm gal}/r_{\rm gal} = 1/H_0 = 14 \times 10^9$ yr $= 14$ Gyr ago

  note **"Hubble time"** useful timescale even to non-egoists!

$$t_{\rm H} \equiv \frac{1}{H_0}$$

  sets scale of $\sim$ "expansion age" of U

can also identify a characteristic lengthscale

Q: suggestions?

limiting speed: c

fastest explosion debris goes farthest $v_{\text{max}} = c = H r_{\text{max}}$

at characteristic distance:

$$r_{\text{max}} = \frac{c}{H_0} \tag{9}$$

this is the "**Hubble length**"

$$d_H \equiv \frac{c}{H_0} = c t_H = 3000\ h^{-1}\ \text{Mpc} = 4200\ \text{Mpc} \tag{10}$$

a useful lengthscale even to non-egoists!

sets $\sim$ size of *observable* U

also: recall homogeneity onset at $\gtrsim 10$ Mpc $\ll d_H$

Q: which means?