Astro 596/496 PC
Lecture 3
Jan 18, 2008

Announcements:
- Preflight 1 due Friday, 12 noon

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?
Cosmological Principle
Q: namely?

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

The Universe to Zeroth Order: Cosmological Principle

Observations teach us that
- at any given 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 given 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:
  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
$\longrightarrow$ large-scale spatial behavior maximally simple

Cosmic Kinematics

Slipher, Hubble 1920's: all 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**

$$z = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}} \qquad (1)$$

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 Relativity/Particle Units I

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

i.e., $v_{\text{fancy}} = v_{\text{ordinary}}/c$
equivalent to putting "$c = 1$"
with rule: insert c factor anytime need v units

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

Edwin Hubble (1929)

`www: Hubble PNAS paper`

`www: original, old-school Hubble diagram`

speed-distance correlation: linear

$$v \propto r \tag{2}$$

Hubble: $v = Kr$

but isotropy implies *Q: what?*

Hubble's Law

Hubble: $v = Kr$

isotropy $\Rightarrow$ same K in all directions

modern: Hubble's Law

$$\boxed{\vec{v} = H\vec{r}} \tag{3}$$

at present: time t_0 ("sub-0 = today")

measure

$$H_0 = 73 \pm 3 \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{4}$$

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
$H_0(\text{old data}) \sim 50 - 100$ km s^{-1} Mpc^{-1}
Worse still: many cosmo results sensitive to H_0
$\rightarrow$ how to show effect of uncertainties?

Parameterized Uncertainty:
introduce "little h" via

$$H_0 \equiv 100\ h \ \text{ km s}^{-1}\ \text{Mpc}^{-1} \tag{5}$$

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

- back in the day, could only say: $h = 0.5 - 1$
- but now $h = 0.73 \pm 0.03$

Why useful? can write, e.g., $d(z = 0.1) \approx cz/H_0 = 300\ h^{-1}$ Mpc

Today the H_0 nightmare is over, but fossil little-h haunts us still
$\rightarrow$ whenever you see it, think $h = 0.73 \approx 1/\sqrt{2}$

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 $v_{\rm max} = c = H r_{\rm max}$

at characteristic distance:

$$r_{\rm max} = \frac{c}{H_0} \tag{6}$$

this is the "**Hubble length**"

$$d_H \equiv \frac{c}{H_0} = ct_H = 3000\ h^{-1}\ \text{Mpc} = 4200\ \text{Mpc} \tag{7}$$

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?

Egoist/Explosion Model (Milne) is logically possible!
i.e., can fit basic cosmo structure, kinematic data

But...

Q: give a philosophical reason why we don't believe this?

Q: give a physical reason why this treatment can't be right?

Q: give an observational reason why we don't believe this?

Critiques of Cosmic Egoism

We are at the center of the universe?

Philosophically:
• not Copernican ("principle of mediocrity")

Physically:
• haven't included gravity!

Observationally:
• Milky Way, Local Group don't look special
not what expect from center of explosion
compare supernova $\rightarrow$ neutron star, black hole

...yet v pattern makes us look special...