Astro 406

Lecture 27

Oct. 30, 2013

Announcements:

- **PS 8 due Friday**
- ASTR 401:
  Planetarium makeup activity posted, due Nov. 6

Last time: active galactic nuclei (AGN)

Q: why "active"? what's a quasar?

Q: what are they like? similarities, differences among AGN?

Q: what are they?

Supermassive Black Holes

Recall:
MH has supermassive BH: quiet
QSO have supermassive BH: active

turns out:
most or all galaxies have supermassive BH! ...but most quiet
$\rightarrow$ maybe active galaxies are phase in evolution?

BH mass **correlated** with host gal v dispersion: $M_{\mathsf{BH}} \propto \sigma^4$
but Faber-Jackson: spheroid stars: $M_{\mathsf{sph}} \propto \sigma^4$
$\rightarrow$ $M_{\mathsf{BH}}/M_{\mathsf{sph}} \sim const \sim 0.006$
galaxies have constant "supermassive black hole fraction"
$\rightarrow$ supermassive BH formation is part of galaxy formation!

Supermassive Black Holes: Open Questions

How does a $10^{7-8} M_\odot$ BH ($R_{\rm Sch} \sim$ AU)
"know" about the $10^{11-12} M_\odot$ galaxy it lives in (and vice versa)?

How does a SMBH "grow" – what are the "seeds," and how are they "fed"?

- accretion surely plays a role
- SMBH mergers also must occur during galaxy mergers

  `www: binary black hole pair`

Are there any galaxies without SMBH?
Are there any SMBH without galaxies?
Either way, what does this mean?

COSMOLOGY

Cosmology: The Big Picture

the Universe as a physical system

- structure
- dynamics
- composition
- origin
- evolution

Large Scale Structure:

Cosmological Principle

Q: technical definition?

Q: restate in simple language?

Q: how observationally test?

The Logic of the Cosmo Principle

Cosmo Principle:
On large scales ($\gtrsim 30$ Mpc), universe is
- homogeneous $\rightarrow$ smoothly, uniformly spread
- isotropic

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?

Cosmo principle as cosmic democracy:
Universe has no center, no edge
no special places, directions!

Cosmologist Dr. B. Dylan (1964)

I'm just average, common too
I'm just like him, the same as you
I'm everybody's brother and son
I ain't different from anyone
It ain't no use a-talking to me
It's just the same as talking to you.

Cosmological Principle: Implications

- demands enormous regularity

"maximal symmetry" $\rightarrow$ simplifies analysis!

Freidmann-Robertson-(Lemaître)-Walker models

FRW (FRLW) cosmology

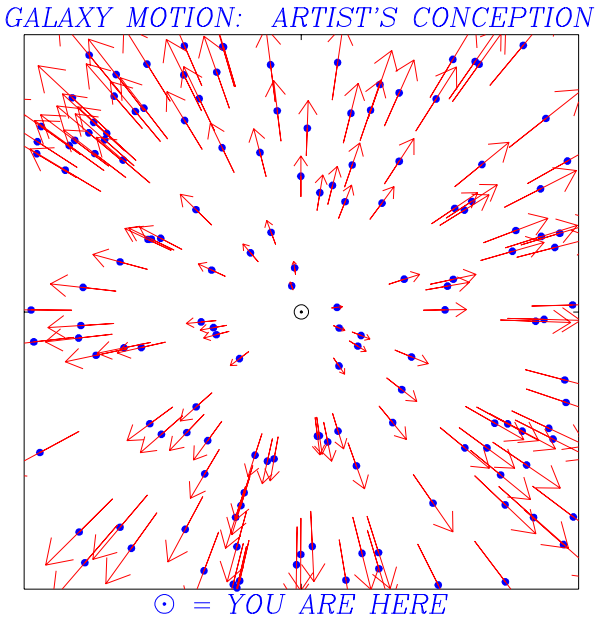
- places stringent constraints on
  (i.e., simplifies!) the possible nature and behavior
  of the Universe and its contents
  i.e., is "the cosmologist's friend"

- "trying to tell us something"
  about how universe formed?
  (e.g., cosmic inflation in early universe?)

Structure + Dynamics: Evolution

observe:

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



Q: how reconcile?

at least 2 logical possibilities...

iClicker Poll: A Cosmic Bomb

imagine all galaxies start at one point: $r = 0$
and at $t = 0$ are *launched in all directions*
with wide *distribution of speeds* $v_{\text{gal,init}}$, *coast freely after*

What will we observe today, from center?

A a "shell" – all galaxies at same distance
Hubble fail! Cosmo principle fail!

B Hubble Law! slower galaxies nearby, fast galaxies far away
density set by $v_{\text{gal,init}}$ distribution, maybe not homogeneous

C Hubble Law! slower galaxies nearby, fast galaxies far away
homogeneous density regardless of $v_{\text{gal,init}}$ distribution

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

imagine an explosion at $t = 0$
if galaxies all start at $r = 0$
  and fly away with distribution $v_{\rm gal} = const$
  but we remain at $r = 0$
then $r_{\rm gal} = v_{\rm gal} t_{\rm today}$ fastest $\rightarrow$ farthest!

- $v_{\rm gal} = H_0 r_{\rm gal} \propto r_{\rm gal}$: recover Hubble's law!
- *in this model*, can calculate *age of Universe* as
  $t_{\rm today} = t_{\rm H} = 1/H_0 = 14 \times 10^9$ yr $= 14$ Gyr ago
  $t_{\rm H}$: **Hubble time** (still useful timescale even to non-egoists!)

Logically possible! 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:
- coasting galaxies unphysical – 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

The Magic of Hubble

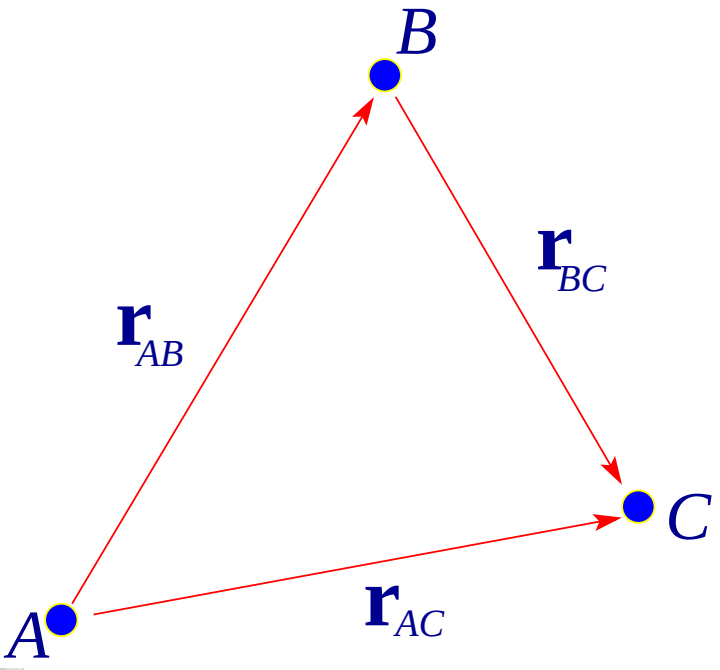
consider three arbitrary cosmic points:

$$\vec{r}_{BC} = \vec{r}_{AC} - \vec{r}_{AB}$$

Assume A sees Hubble's law:

- $\vec{v}_{AB} = H\vec{r}_{AB}$
- $\vec{v}_{AC} = H\vec{r}_{AC}$

Then ask: *what does B see? C?*



find velocities relative to B:

$$\vec{v}_{BC} = \vec{v}_{AC} - \vec{v}_{AB} = H(\vec{r}_{AC} - \vec{r}_{AB}) = H\vec{r}_{BC}$$

This is awesome!

Q: why? What have we proven?

we have shown:
if A sees Hubble's law, then so do (arbitrary) B and C
thus: if *any* observer measures Hubble's law
then *all* observers will measure Hubble's law!

so: Hubble law implies
$\rightarrow$ *all galaxies recede according to same law*
$\rightarrow$ no need for center, space has no special points

Moreover: Hubble law is *only* motion
which preserves homogeneity and isotropy
i.e., *any* other motion breaks cosmo principle
...but Hubble law is exactly what's observed!

Revolution Re-Re-Re-Visited

Copernican Revolution I (Copernicus, 17th Century):
Earth is one typical planet among many
not center of solar system
Copernican Revolution II (Shapley, earth 20th Century):
Sun is one typical star among many
not center of Milky Way Galaxy
Copernican Revolution III (Hubble, 1920's):
Milky Way is one typical galaxy among many
Universe much larger than previously thought
Copernican Revolution III (Zwicky, Rubin, et al., late 20th century):
most matter in the U is weakly interacting dark matter
we are not even made of the dominant stuff
Copernican Revolution IV (Einstein et al, 20th century):
Universe is homogeneous on large scales,
and has no center
... stay tuned for more...

Describing Expansion

the meaning of Hubble Law: Take 2

2. Einstein interpretation:
using General Relativity:
Universe is expanding
all galaxies receding from all others
bold, strange idea!

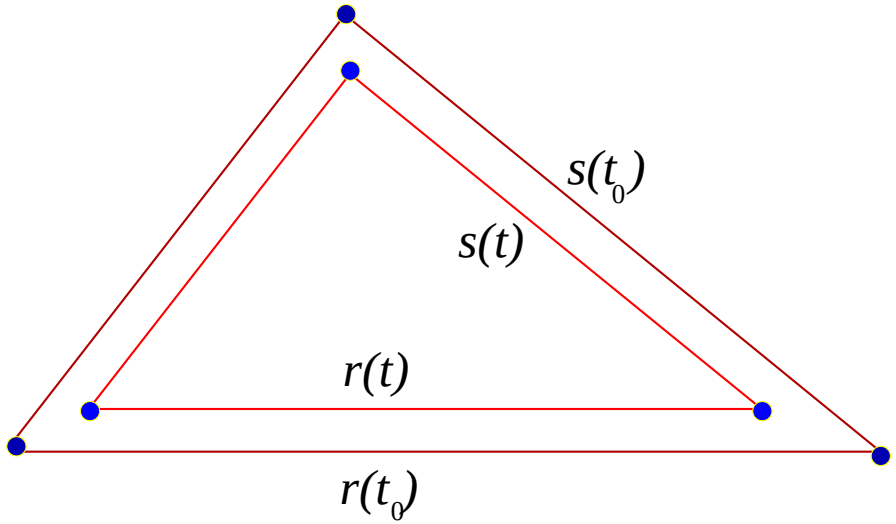
In fact: Einstein himself initially found it unacceptably strange
in 1917, modified GR equations with "fudge factor"
$\rightarrow$ "cosmological constant" Λ designed to keep Universe static
after Hubble's 1929 work, Einstein allegedly said this was
his "greatest blunder"
...but wait a few lectures...

consider arbitrary triangle defined by 3 observers at t_0

if homogeneous and isotropic expansion

expanded Δ always *similar to* original Δ

Q: what are similar triangles? why must this hold?



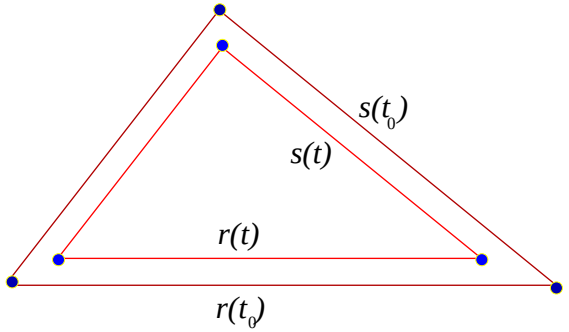
Q: connections among r's and s's?

similar: triangle sides keep same ratios,
so must have

$$\frac{r(t)}{r(t_0)} = \frac{s(t)}{s(t_0)}$$

holds for any triangle,
so side length ratio depends only on time t:

$$a(t) = \frac{r(t)}{r(t_0)} = \frac{s(t)}{s(t_0)}$$



Q: and so?

side length ratio depends only on time t:

$$a(t) = \frac{r(t)}{r(t_0)} = \frac{s(t)}{s(t_0)}$$

which measn: over any time interval *all lengths grow by same factor*

$a(t)$ must be **universal scale factor**

my convention: a dimensionless
scale factor value today: $\boxed{a(t_0) = 1}$

Note: $r(t_0) \equiv r_0$ is "comoving" coordinate
my convention: value at present epoch t_0

Expansion: Einstein $\rightarrow$ Hubble

transparency demo: photocopy universe

for two arbitrary observers (e.g., "galaxies")
scale factor gives distances
$\vec{r}(t) = \vec{r}_0 a(t)$
so velocity is

$$\vec{v}(t) = \dot{\vec{r}} = \vec{r}_0 \dot{a} = \frac{\dot{a}}{a}\, a\vec{r}_0 = H(t)\vec{r} \qquad (1)$$

$\Rightarrow$ Hubble law!
now interpret "Hubble parameter"
as **expansion rate** $H(t) = \dot{a}/a$

present value (subscript 0):

$$H(t_0) \equiv H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \qquad (2)$$