Astro 406
Lecture 31
Nov. 8, 2013

Announcements:

- **PS 9 due now**
- **PS 10 due next Friday**
- ASTR 401: make appointment to meet

Last time: cosmodynamics–the Friedmann equation(s)

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi}{3}G\rho - \frac{\kappa c^2}{R_0^2 a^2} \quad (1)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\left(\rho + 3P/c^2\right) \quad (2)$$

Q: what do κ, R_0, ρ, P represent?
Q: which quantities are variables? which are parameters?
Q: how is a matter-only universe special? a flat universe?
Q: what is needed to make $\dot{a} = 0$ and $\ddot{a} = 0$? implications?

in Friedmann:

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi}{3}G\rho - \frac{\kappa c^2}{R_0^2 a^2} \quad (3)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\left(\rho + 3P/c^2\right) \quad (4)$$

- $\rho = \varepsilon_{\text{tot}}/c^2 = (\varepsilon_{\text{matter}} + \varepsilon_{\text{rad}} + \cdots)/c^2$: mass-energy density non-pointlike version of $E = mc^2$
- $P = P_{\text{tot}} = P_{\text{matter}} + P_{\text{rad}} + \cdots$: total cosmic pressure

a static universe? with matter and without Λ:

- can make $\dot{a} = 0$ if $\kappa = +1$ and R_0 "tuned" so curve term cancels density term
- but even then: still have $\ddot{a} < 0$ $\to$ universe will evolve

a static universe is impossible with matter and without Λ!

$$
\begin{aligned}
\kappa \frac{c^2}{R_0^2 a^2 H^2} &= \frac{\rho}{3H^2/8\pi G} - 1 && (5)\\
&= \frac{\rho}{\rho_{\text{crit}}} - 1 && (6)\\
&\equiv \Omega - 1 && (7)
\end{aligned}
$$

Also note: κ fixed once and for all

$\rightarrow$ if $\Omega < 1$ *ever*, stays this way *always*! (same if < 1)

$\rightarrow$ if $\Omega = 1$ *ever*, stays this way *always*!

Even better: can measure ρ_0, H_0

$\rightarrow$ can find $\rho_{\text{crit},0}$

$\rightarrow$ and then find Ω_0

★ Ω_0 *is a measurable number!*

★ *geometry of the universe knowable!*

Future Expansion

Friedmann says

$$H^2 = \frac{8\pi}{3} G\rho - \frac{\kappa c^2}{R_0^2 a^2} \tag{8}$$

for a universe with *matter and radiation*

consider the cosmic future: $a > 1$

Q: if $\kappa = 0$, what is future cosmic expansion? cosmic fate?

Q: what if $\kappa = -1$: future expansion and fate?

Q: what if $\kappa = +1$: future expansion and fate?

Density and Destiny

Friedmann and the cosmic future:

$$H^2 = \frac{8\pi}{3} G\rho - \frac{\kappa c^2}{R_0^2 a^2} \geq 0 \qquad (9)$$

if $\kappa = 0, -1$: $H^2 > 0$ for all a
$\rightarrow$ no max a $\rightarrow$ *fate: expand forever* $\rightarrow$ **big chill**

if $\kappa = +1$: matter + rad U eventually curvature dominated
expand to max a, instantaneously $H = 0$, $\dot{a} = 0$
but $\ddot{a}/a < 0$ always if matter + radiation
so then $\dot{a} < 0$
$\rightarrow$ *fate: recollapse* $\rightarrow$ **big crunch**!

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So: $\kappa \Leftrightarrow$ Fate of Universe $\Leftrightarrow \Omega_0$
$\rightarrow$ density is destiny! weight is fate!

Weighing the Universe

Fate and geometry of U $\rightarrow$ urgent question:
What is the value of Ω_0?

since $\Omega = \rho/\rho_{\text{crit}}$
with $\rho_{\text{crit}} = 3H^2/8\pi G$
we know today:

$$\rho_{\text{crit},0} = 10^{-29}\ \text{g/cm}^{-3} \tag{10}$$

$$= 1.4 \times 10^{11}\ M_\odot\ \text{Mpc}^{-3} \tag{11}$$

so fate and geometry boil down to
★ *what is $\rho_{0,\text{total}}$?*
★ how does it compare to $\rho_{\text{crit},0}$?

Finding Ω_0 Part 1: I Think, Therefore $\Omega = 1$

$\Omega = \rho/\rho_{\rm crit} \sim \rho(t)/H^2(t)$ *evolves* with time
if $\Omega < 1$ or > 1 then
  driven either to $\Omega \rightarrow 0$ or ∞ *Q: why?*
unless $\Omega = 1$, in which case stays 1 always

$\Omega = 1$ is only stable value

do the experiment: look around room
$\Rightarrow$ clearly $\Omega \neq 0, \infty$
which means either:

- $\Omega = 1$! , or
- conspiracy *Q: what is nature of conspiracy?*

Finding Ω_0 Part 2: Mass from Light

Procedure:

1. find **fair sample** of U., measure!
2. want: M, $V \to \rho$

   but usually measure L, V

so:

- find *cosmic luminosity density* $\mathcal{L} = L/V$ (as in PS8)
- multiply by *mass-to-light ratio* $M/L \equiv \Upsilon$
- find *mass density* $\rho = \Upsilon \mathcal{L}$

Galaxy surveys (most complete: SDSS):

$\mathcal{L} = \langle L \rangle n_{\rm Gal} \sim 2 \times 10^8 \ h \ L_\odot \ {\rm Mpc}^{-3}$

Need mass-to-light ratio Υ for "fair sample" of U.

Q: what counts as a fair sample?

Q: what might qualify? what doesn't qualify?

Fair samples?

galaxy dark halos: $\Upsilon_{\rm halo} \lesssim 25 h M_\odot / L_\odot$
$\rightarrow \Omega_{\rm halo} \lesssim 0.02 \ll 1$

Q: what does this mean physically?

Q: anybody have any problems with this?

not at all clear that galaxy halos are fair samples
have found larger mass-to-light in other systems

Local Group

from Local Group timing: $\Upsilon_{\rm group} \sim 100 \ M_\odot/L_\odot$
$\rightarrow \Omega_{\rm group} \sim 0.07 h^{-1}$

Q: are we done? other mass-to-light values?

Clusters: $\Upsilon_{\text{cluster}} \sim 300 h M_\odot / L_\odot$
$\rightarrow \Omega_{\text{cluster}} \sim 0.25 h^{-1} \sim 0.3$

In fact: clusters are the largest bound objects
$\rightarrow$ we expect them to have just formed
and to have democratically collected their contents
$\rightarrow$ we think clusters are fair samples
$\Rightarrow$ we think they give the matter density of the Universe

$\star$ matter (including DM!) accounts for only $\sim 30\%$
of critical density
$\rightarrow$ if this is it, then the answer would be
1. hyperbolic (open, infinite volume) geometry
2. fated to expand forever

however: we have a way to know the answer
...and the results are in!

iClicker Poll: Preferred Cosmic Geometry

Vote your conscience!

putting aside what the data tell us

What cosmic geometry would you prefer to live in?

A $\kappa = +1$: spherical, finite volume
parallel lines always meet

B $\kappa = 0$: Euclidean, infinite volume
parallel lines maintain same distance

C $\kappa = -1$: hyperbolic, infinite volume
parallel lines always diverge

iClicker Poll: Preferred Cosmic Fate

Vote your conscience!

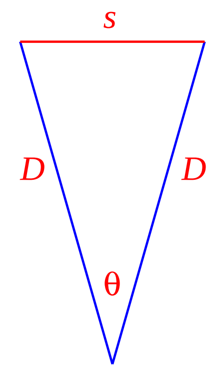
putting aside what the data tell us
What cosmic destiny would you prefer?

A expand forever

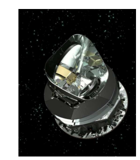
B expand forever, but just barely

C recollapse

Finding Ω_0 Part 3: Cosmic Geometry



since 2003: can directly measure cosmic geometry!
using "blobs" in the *cosmic microwave background*
`www: CMB sky as seen by Planck`
basic idea: blobs have known physical size s
and are at known distance D
$\rightarrow$ *geometry/trig predicts blob angle* θ on sky
but we can *measure* θ $\rightarrow$ see if Euclidean result is right!



Good news
CMB (with other data) $\rightarrow$ $\Omega_0 = 1.0005 \pm 0.0033$!
trying to tell us: $\Omega_0 = 1$!!

Weird news:
CMB (+other data) confirms $\rightarrow$ $\Omega_{\text{matter}} \approx 0.30$ (including DM!)

Q: but this must mean?

Cosmic Bookkeeping

CMB and clusters tell us:

- $\Omega_{\rm matter,0} \approx 0.30$ (including DM!)

but the CMB also finds a flat (Euclidean) universe

- $\Omega_0 = 1.0005 \pm 0.0033$

But $\Omega = \rho_{\rm tot}/\rho_{\rm crit} = \Omega_{\rm matter} + \Omega_{\rm rad} + \ldots$
and we measure $\Omega_{\rm rad} = 5 \times 10^{-5}$: negligible (today)
so we are forced to infer that today $\rightarrow$ $\Omega_{\rm other} = 0.70$?!?

Friedmann Revisited

we have seen that the Universe is *flat*
i.e., the three-dimensional space obeys *Euclidean geometry*

note that this allows us to simplify the Friedmann eq.
because our Universe has $\kappa = 0$:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \tag{12}$$

- no pesky curvature term
- obviously $\rho > 0$ (look around), so $H > 0$ always
  cosmic expansion will never stop
  we are fated to a *big chill*

...or worse. More later on this.

The Cure for Ignorance is Data!

21st century cosmology tell us:
70% of cosmic mass-energy today is in an unknown form
not matter–including dark matter!
not radiation–including neutrinos!

Spoiler alert: we do not know what this unknown stuff is.
In instructors opinion: we don't even have good ideas
sure, we have ideas, but not good, compelling ideas

What *do* we know?

- must be *dark* (or we would have seen it already)
- has to gravitate: must have *mass-energy*
  ...but not be matter (i.e., can't be dark matter), nor radiation

$\Rightarrow$ **dark energy**

When faced with ignorance: *get more data!*

Dark Energy and Cosmic Expansion

measure properties of dark energy
e.g., how does dark energy change as the Universe expands?

good news: simplified Friedmann shows the way

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho = \frac{8\pi G}{3}(\rho_{\text{matter}} + \rho_{\text{rad}} + \rho_{\text{DE}}) \tag{13}$$

measuring expansion history $H(t)$
– or equivalently $H(z)$
will tell us how ρ_{DE} evolves!

Cosmic Expansion History

we want to probe dark energy via expansion history $H(t)$
i.e., measure expansion rate at different cosmic epochs

how to do this?

rough sketch of basic idea (right in sprit, but oversimplified):
use Hubble relation $v = cz \approx H \ D$

- find objects observable at wide range of times, and for each:
  1. measure redshift z
  2. measure distance $D(z)$
- infer expansion rate

$$H(z) = \frac{cz}{D(z)} \tag{14}$$

- read off expansion history by seeing change with z

Q: what's the hardest part of this procedure?

Supernovae and Cosmodynamics

goal: measure expansion at different z
$\rightarrow$ see how H evolved $\rightarrow$ probe ρ

key tool: **standard candle**
that is: an object of *known* luminosity L

procedure:
- find candle (and be sure it standard!) $\rightarrow$ know L
- measure flux F
- solve for "luminosity distance"

$$D_{\rm lum} = \sqrt{\frac{F}{4\pi L}} \qquad (15)$$

need objects which:
- have fixed L indep of z, environment
- can see at high $z \rightarrow$ high L

$\rightarrow$ **supernova explosions**

Supernova Zoology: A Tale of Two Types

Massive star explosions $\to$ *SN: Type II*
bright, but: L varies w/ mass, metallicity
$\Rightarrow$ diversity is interesting but *bad for standard candle*

SN Type Ia:
`www: SN Ia images, UIUC simulations`
white dwarf explodes due to binary companion
accretion or merger?
WD $\to$ ^{56}Ni (radioactive) $\to$ ^{56}Fe
decay sets $L(t)$ $\to$ *standard candle!*

`www: SN 1994D` low-z
`www: SN subtraction image` medium-z
`www: HDF subtraction image` high-z