Astro 507

Lecture 14

Feb. 21, 2014

Announcements:

- **Problem Set 2 due now**
- **Preflight 3 posted today, due next Friday 9am**

Last time: reconciling $\Omega_0 = 1$ with $\Omega_m \approx 0.3$

Q: strategy? observables?

Q: what's a SN Ia?

Q: why are SNe Ia standard-ish candles? why not? worries?

Strategy: Cosmic Dynamics Reveal Cosmi Contents

Friedmann:

$$H(z)^2 \overset{\text{flat}}{=} \frac{8\pi G}{3}\left[\rho_{\mathrm{m},0}(1+z)^3 + \rho_{\mathrm{other}}(z)\right] \tag{1}$$

measure $H(z) \to$ probe ρ_{other} if it exists

observables: standard candle $\to$ luminosity distance

$$d_{\mathrm{L}}(z) \overset{\text{flat}}{=} (1+z)\int_0^z \frac{dz}{H(z)} \tag{2}$$

measure d_{L} at many z, then:

$$d_{\mathrm{L}}(z+\Delta z) - d_{\mathrm{L}}(z) = (1+z)\int_z^{z+\Delta z} \frac{dz}{H(z)} \approx (1+z)\frac{\Delta z}{H(z)} \tag{3}$$

Type Ia Supernovae: "Standardizable" Candles

Type Ia events: best candidates on balance (for now)

- empirically (low-z) closest to std candles
- typically ~ 1 mag brighter than SN II $\rightarrow$ can probe higher z
- ...but check for systematics!

Type Ia light curves (low-z): *E Pluribus Unum*

light curve $L(t)$ same basic shape–rise, fall

... but spread in timescale ($\sim$ FWHM) & peak L

... but these are tightly *correlated*!

$\rightarrow$ $L(t)$ spread can be empirically fit with 1 parameter

$\Rightarrow$ *scaled* light curves $\approx$ identical! `www: light curves`

$\Rightarrow$ "**standardized**" candles!

Supernova Cosmology Campaigns

Automated searches:
▷ digital sky scans $\sim$ 3–4 weeks apart
▷ subtraction $\rightarrow$ SN Ia, max light
▷ followup to get spectra as dims
`www: SN images, spectra`

The Pioneers

Supernova Cosmology Project	High-z Supernova Search
starting with SN 1992bi:	Starting with SN 1995K:
• $\sim$ 100 SN Ia	• $\sim$ 50 SNe
• $0.15 < z < 1.2$	• $0.3 < z < 1.2$

⋆ Hubble Space Telescope: fewer but very high-z events
Riess et al (2004): 16 SN Ia
• $0.6 < z < 1.6$; highest-z sample
Riess et al (2007), GOODS survey with ACS: 13 new SN Ia
• $0.5 < z < 1.4$

Supernova Legacy Survey (2010) analysis of 472 SN Ia

- 123 low z
- 93 SDSS
- 242 SNLS
- 14 HST

Combine low-z + high-z data, then:

1. do cosmology
2. worry

Luminosity Distance and Acceleration

for a flat universe

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

so $d_L(z) \sim \langle (1+z)z/H(z) \rangle$ traces expansion rate history

strategy:

- measure d_L over large z range
- infer *evolution/change in* $\langle 1/H \rangle$

Q: What does this give us?

Q: What are basic trends?

Change in $1/H \to$ change in H:

$\Rightarrow$ *acceleration vs deceleration of scale factor*

in fact, can show d_L (and d_A!) sensitive to

deceleration parameter

$$q \equiv -\frac{\ddot{a}/a}{(\dot{a}/a)^2} \tag{4}$$

Q: why conventional $-$ sign?

present value: q_0

but in general q can evolve

Acceleration and Luminosity Distance

Can show

$$d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{1+z'} e^{-\int_0^{z'} q(u)\, d\ln(1+u)}$$

- cosmological details only enter via $q = -(\ddot{a}/a)/(\dot{a}/a)^2$
- uses only RW, not Friedmann: result indep of GR!

Compare different "universes" – i.e., models with different $q(z)$

$$\frac{d_L(z)_{\text{universe 1}}}{d_L(z)_{\text{universe 2}}} = \frac{\int_0^z \frac{dz'}{1+z'} e^{-\int_0^{z'} q(u)_{\text{universe 1}}\, d\ln(1+u)}}{\int_0^z \frac{dz'}{1+z'} e^{-\int_0^{z'} q(u)_{\text{universe 2}}\, d\ln(1+u)}}$$

Compare two possible universes

- non-accelerating: $q = 0$
- decelerating: $q > 0$

Q: which has bigger d_L at fixed z and fixed H_0?

Q: what if positive acceleration? `www:` d_L `plots`

SN Ia Survey Predictions

Luminosity distance: $d_L(z) = (1+z) r_{\text{com}}(z)$

- $r_{\text{com}} \overset{\text{flat}}{=} \int dt/a(t) = \int da/a\dot{a}$: closest in decelerating U
  $\Rightarrow d_L^{\text{decel}} < d_L^{\text{non-accel}} < d_L^{\text{accel}}$
- candle brightness: $F_{\text{decel}} > F_{\text{non-accel}} > F_{\text{accel}}$

but since gravity is attractive, should slow expansion...

▷ deceleration: $q > 0$
faster H in past $\rightarrow$ smaller $1/H$
$\rightarrow$ predict $d_L(\text{obs}) < d_L(\text{non}-\text{accel})$
$\rightarrow$ predict $F_{\text{obs}} > F_{\text{non-accel}}$:
expect std candles *brighter* than in $q = 0$

SN Ia Survey Observations

`www: SNIa survey data`

Exactly the *opposite* of predictions!

★ standard candles **appear faint!**

in magnitudes, $m_{\text{obs}} > m_{\text{non-accel}}$

flux $F_{\text{obs}} < F_{\text{non-accel}}$

★ $d_L(\text{obs}) > d_L(\text{non}-\text{accel})$

Q: possible explanations?

...(at least 3 distinct classes)

Q: pros and cons?

Q: how to observationally test?

Faint SN Ia: Whodunit?

⋆ **Blame the Observations**
maybe: SN Ia are *not* reliable standard(izable) candles
i.e., $m(\text{obs}) \neq m(\text{std candle})$
such that $L_{\text{SN}}(\text{high} z) < L_{\text{SN}}(\text{low} z)$ *systematically*

⋆ **Blame Einstein**
observations correct, but
expectations based on gravity theory = GR
maybe: GR incorrect/incomplete

⋆ **Blame the Universe**
observations correct, and GR correct as well, so
infer existence of new cosmic contents which create acceleration
e.g., acceleration points to an accelerant!
maybe: Friedmann OK, but missing terms
i.e., beyond matter (including DM!) and radiation
new source(s) of ρ, P

What is to be done?

At face value
• SN Ia ⇒ U. is accelerating
• RW+Einstein ⇒ need new cosmic components
For now: assume these are true; then...

Our Mission
quantify–and ultimately identify–the new stuff
see if we can live with the consequences

But don't forget:
▷ keep checking SN Ia systematics
▷ don't dismiss gravity beyond Einstein:
GR may itself be a limiting case of larger theory
just as Newtonian gravity is limit of GR

First step:
Q: Friedmann–what are conditions for acceleration?

Acceleration in a FLRW Universe

Recall:

Cosmo principle (RW metric) + GR

= Friedmann

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right) \tag{5}$$

But SNIa $\rightarrow$ $\ddot{a} > 0$:

$$P < -\frac{1}{3}\rho c^2$$

Q: implications? interpretation?

cosmic acceleration demands $\boxed{P < -\rho c^2/3}$

Cosmic pressure is

★ non-negligible

★ negative! *Q: meaning?*

★ (for GR experts) violation of strong energy condition
$\rho + 3P \geq 0$ fails!

Exotic substance mandatory!

- NR matter and/or radiation in *any* form
  even wierdo particle dark matter (WIMPs, axions, ...)
  have $P \geq 0$: inadequate!
- new accelerant must be *dark*
  i.e., has not been undetected in EM radiation
- simplest solution is oldest...

Acceleration and the Cosmological Constant

Originally: Einstein modification of GR
to allow for *static* universe: $\ddot{a} = \dot{a} = 0$

- forced to introduce new constant of nature
  cosmological constant $\boxed{\Lambda}$

- $[\Lambda] = [\text{length}^{-2}]$; alters cosmic geometry

- spoils GR $\rightarrow$ Newtonian limit: instead,

$$\nabla^2 \phi = 4\pi G \rho - \frac{c^2}{3} \Lambda$$

Q: what does this do to Newtonian gravity?
Q: why isn't this immediately fatal?

Cosmo-Sociology: The Checkered History of Λ

Λ often invoked to solve cosmo problems,
then abandoned when observations improved

example: early measurements gave $H_0 \sim 500 \text{ km s}^{-1} \text{ Mpc}^{-1}$
$\rightarrow t_{\rm H} \sim 2$ Gyr $\ll$ age of Earth!
Lemaître (1931): Λ can give "loitering" Universe
quasi-static for a long time, then begins expanding recently

"My greatest blunder."
– A. Einstein, allegedly, on inventing Λ

"The cosmological constant is the last refuge of scoundrels."
– famous Chicago cosmologist and current Λ enthusiast, circa 1990

Living with Λ

With $\Lambda \neq 0$, new term in both Friedmann eqs

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa c^2}{R^2 a^2} + \frac{c^2}{3}\Lambda \qquad (6)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right) + \frac{c^2}{3}\Lambda \qquad (7)$$

Note appearance & sign in acceleration

$\Rightarrow$ Λ an "accelerant" $\rightarrow$ "antigravity"

Q: intuitive reason? Hint: original purpose?

convenient to introduce $\Omega_\Lambda = \Lambda c^2 / 3H^2$

allows easy comparison of Λ term with others

Q: but you can guess which larger, based on observed accel?

The Data: Λ Emerges

SN Ia data in Λ cosmology:

- allow for $\Omega_\Lambda = \Lambda c^2/3H^2 \neq 0$
- find best fit to d_L data:

"concordance universe"

`www:` $\Omega_\Lambda - \Omega_\mathrm{m}$ `plane`

$$\boxed{\Omega_\Lambda \simeq 0.7 \qquad \Omega_\mathrm{m} \simeq 0.3} \tag{8}$$

Q: why is this amazing!