Astro 507

Lecture 15

Feb. 27, 2020

Announcements:

- **Preflight 3 was due today**
- **Problem Set 3 posted, due next Friday March 6**

Last time: began Modern Cosmology–Homogeneous Edition

Pressing Question: how to reconcile $\Omega_{\rm m} \sim 0.3$ and $\Omega_0 = 1$?

Strategy: Cosmic Dynamics Reveal Cosmic Contents

Friedmann:

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

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

observables: standard candle $\rightarrow$ luminosity distance

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

measure d_{L} at many z, then:

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

Supernova Zoology 101

- **Type II* (Core-Collapse) Supernovae**
  massive star $\gtrsim 8 - 10 M_\odot$ gravitational collapse
  optical (baryonic) explosion: $E_{\rm vis} \sim 10^{51}$ erg
  but most energy released in neutrinos: $E_\nu \sim 3 \times 10^{53}$ erg
  neutron star/black hole remnant

  *Types Ib and Ic events also due to core-collapse

- **Type Ia (Thermonuclear) Supernovae**
  binary system: white dwarf and companion
  WD accretes $\rightarrow$ pushed over Chandrasehkar limit
  i.e., drive $M_{\rm WD} > 1.4 M_\odot \rightarrow$ gravitationally unstable
  thermonuclear detonation $E_{\rm exp} \sim 10^{51}$ erg

Q: pros and cons of each Type for cosmology?

Supernova Cosmology: The Good, the Bad, and the Ugly

Type II Supernovae

Pro

- Understand basic physics:
  most E_{SN} in neutrinos
  saw 1987A neutrinos
  confirmed basic picture

Con

- Don't understand optical explosion:
- $E_{\mathrm{vis}} \sim 1\% E_{\mathrm{SN}}$ tough!
  models often don't explode!
- core collapse: range of masses, E_{SN}

$\Rightarrow$ diverse range of L $\Rightarrow$ candle not std
occur in $\star$-form regions $\rightarrow$ obscured

Type Ia Supernovae

Pro

- Chandra limit $\sim$ fixed mass
  $+$ nuke binding $\sim$ fixed
  $\approx$ fixed E release
  $\Rightarrow$ fixed $L(t)$: std candle!
- low-z SN Ia nearly identical $L(t)$
- outside $\star$-form: less(?) obscured

Con

- Don't understand basic
  scenario: who is companion?
  giant? another WD?
  astrophysical "black box"
- low-z Ia *not* identical $L(t)$

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: $d_L(z) = (1+z) r_{\rm com}(z)$

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

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

▷ deceleration: $q > 0$

faster H in past $\to$ smaller $1/H$

$\to$ predict $d_L(\text{obs}) < d_L(\text{non} - \text{accel})$

$\to$ predict $F_{\rm obs} > F_{\rm non-accel}$:

expect std candles *brighter* than in $q = 0$