Cosmology & Type Ia supernovae

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Observational cosmology

Observing around us and build models to explain what we perceive

The universe is the object of study
Measuring distances
Measuring velocities

Redshift

\[ \frac{\Delta \lambda}{\lambda_0} \sim \frac{\Delta v}{c} \]

“run away” velocity
The further the galaxies are
Hubble Law
recession speed = $H_0 \times \text{distance}$
Hubble Law

recession speed = $H_0 \times$ distance
The further the galaxies are, the faster they run away from us.
So, we are at the Center...

**Hubble’s Law:** \( v = H \cdot d \)

- \( d = 0 \) miles
- 250 miles
- 500 miles

- \( v = 25 \text{ mph} \)
- 50 mph
... and yet, maybe not

Hubble's Law: $v = H d$

d=0

25 miles $\rightarrow$ 500 miles

$v=$

25 mph $\rightarrow$ 50 mph

Maybe the Universe is expanding
The Model we chose:

Assuming the Cosmological Principle:
\[
ds^2 = g_{\mu\nu} dx^\mu dx^\nu
\]
\[
= -c^2 dt^2 + a^2(t) \left[ \frac{dr^2}{1-kr^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2) \right]
\]
\[
= -c^2 dt^2 + a^2(t) \, dl_{(3)}^2
\]

Now throw in some physics (GR):

**energy density**

\[
H^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \left( \rho - \frac{k c^2}{a^2} \right)
\]

\[
\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3 p) / c^2
\]

**critical density**

Define \( \rho_c = 3H_0^2 / 8\pi G \), treat everything as an ideal fluid \( p = \frac{w}{1+w} \times \rho \):

\[
\frac{H^2}{H_0^2} = \sum \Omega_i a^{-3(1+w_i)} + \Omega_k a^{-2}
\]
Going further with SNe Ia

Very bright objects

Very standard objects

Objects easy to recognize
So, why is that hard?
Finding SNe Ia

Sky ain't no small

1 SN Ia per galaxy per millenium
Telescope size matters... 

... as well as the observed volume.
Comparing images

Supernova SNLS-03D4ag
Many candidates, few interesting targets
So, what's so hard?

1) Finding the SNe Ia
Identifying SNe Ia

And redshift measurement
So, what's so hard?

1) Finding the SNe Ia

2) Identifying the SNe Ia
Observing SNe Ia

Optical filters to integrate the light

\[ F = \frac{L}{4\pi d^2} \]

\[ \mu = 5 \log_{10} \left( \frac{d_L}{10pc} \right) \]
Accounting for CCD “features”
Extracting the flux of the SN Ia

The fitted model $M$ for image $i$ at position $p$ is given by:

$$M_{i,p} = \left\{ f_i \times \text{PSF}(\bar{x}_p - \bar{x}_{SN}) + \text{gal}_\text{ref} \right\} \otimes K_i \Bigg|_{p} + s_i$$

- 0 Flux before explosion
- Point Spread Function
- Host galaxy flux
- Sky variation
- PSF variation
Calibrating the flux

Same stars, same flux
Relative calibration

Flux reference
ergs / ADUs

Flux calibration

Supernova
Need an absolute flux reference

HST observations and DA White Dwarf models

Absolute flux reference
Most of the time no absolute standard in the field.

Secondary standards for relative calibration

Atmospheric transmission

Filters

And the telescope...
The SN Ia is **redshifted**

But we need it **restframe**

We need to know how much light would have ended in the **RESTFRAME FILTERS**
A spectral model

$S(\lambda, \phi) = x_0 S_0(\lambda, \phi) \left[1 + x_1 S_1(\lambda, \phi) \right] \exp[-c CL(\lambda)]$

Time evolution

Color measurement

Plain lines = Light curve fit

Forward fitting approach of a deconvolution problem

Yields $x_1$ and $c$
So, what's so hard?

1) Finding the SNe Ia

2) Identifying the SNe Ia

3) Measuring and calibrating SNe Ia fluxes
At least, we are done!

... But for one question: what is a type Ia supernova?
What can we learn from imaging?

Radioactively powered light curves
most important chain: $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$

- Light curve duration given by standard diffusion time:
  $$t_d \sim \left[\frac{M\kappa}{v_c}\right]^{1/2}$$
- Luminosity estimate from radioactive energy deposition:
  $$L_{ni} \approx \frac{M_{ni}e_{ni}}{t_{ni}} e^{-t_d/t_{ni}}$$

- $^{56}\text{Ni}$ (7 day half-life) $\rightarrow ^{56}\text{Co}$ (77 day half-life) $\rightarrow ^{56}\text{Fe}$

Old and young hosts
No remnant
What can we learn from the spectra?

Expansion velocity $>15000 \text{km/s}$

Intermediate mass elements (Si, S, Mg, Ca ...)

$^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$
Thermonuclear explosion of one... or two White Dwarves

Very difficult to model

- stellar evolution (>10^6 years)
- explosion (seconds/hours)
- expanding ejecta (months)

\[ \rho(r), T(r), A(r) \text{ at ignition/collapse} \]
\[ \rho(x,y,z), v(x,y,z), T(x,y,z), A(x,y,z) \text{ in free expansion} \]

- hydrodynamics, equation of state
- nuclear burning, neutrino transport
- photon transport
- matter opacity
- thermodynamics
- radioactive decay

- neutrinos
- grav. waves
- x-rays, γ-rays
- optical spectra
- light curves

\[
\frac{n_i}{n_j} = \frac{g_i}{g_j} \exp(-\Delta E/kT)
\]

\[
\frac{\partial n_i}{\partial t} = \sum_{j \neq i} (n_j R_{ji} - n_i R_{ij}) + \sum_{j \neq i} (n_j C_{ji} - n_i C_{ij}) + \sum_{j \neq i} (n_j G_{ji} - n_i G_{ij}) = 0
\]

Non-stationary matrix, where \( n \) = number of atomic levels (sparsity depends on number of transitions included)
Only qualitative agreement between models and data

1.4 M\(_{\odot}\) delayed detonation

1.1 M\(_{\odot}\) + 0.9 M\(_{\odot}\) WD merger

Thermonuclear explosion of one... or two White Dwarves
Some “hints” that the environment matters:

- Host metallicity correlated with SALT2 c
- Distance residual correlated with host mass
- Could those depend on $z$?

$$m_{\text{obs}} = M_0 + \mu_0 + \alpha x + \beta c + \mu$$

This will matter for next generation surveys.
Besides, SNe Ia don't explode in a Void

There is dust in galaxies

Dust average properties can depend on $z$

$$m_{obs} = M_0 + \mu_0 + \alpha x + \beta c + \mu$$

And SNe Ia in dust
Next generation of SNe Ia cosmological surveys

Spectroscopic surveys to understand the object

SNLS 5: 500 high redshift SNe Ia vs 200 Nearby SNe Ia

Nearby SNe Ia might become the bottleneck