1 Type Ia Supernovae

The Type Ia supernovae (SN Ia) are the most popular standard candle in cosmology today.

Advantages:

- Can be seen to cosmologically significant distances, $z \sim 1.8$.
- Small dispersion in intrinsic luminosity, $\sim 15\%$ after applying corrections.
- Frequent, transient events – can always observe more.

Disadvantages:

- Subject to extinction.
- Requires relative calibration of fluxes at different wavelengths.
- Physics that determines luminosity not known from first principles, worry may evolve with redshift.
- Very faint in restframe UV, work at $z \geq 1$ requires NIR observations, must be space based due to sky brightness.

So let's get started!

Classification of supernovae. SNe are broken into four types (Ia, Ib, Ic, II) based on their spectra:

- SN II – shows H lines.
- SN Ib – no H lines, but does have He lines.
- SN Ia – no H/He lines, but with Si^+ 6150Å feature (blueshifted Si^+ 6347,6371Å $3s^2 4s - 3s^2 4p$).
- SN Ic – no H/He lines (or very weak He), no Si^+.

Physically correspond to different types of objects: II/Ib/Ic are due to core collapse in massive star, type depends on whether H and He layers have been thrown off (e.g. by stellar wind).

The SN Ia are due to thermonuclear explosion of C/O white dwarf or some variation thereof. (Variations: white dwarf is accreting, reaches Chandrasekhar mass; two white dwarfs, etc. Progenitor still under debate.) Common argument is that Chandrasekhar mass $1.4 M_\odot$ determines "standard candle" nature but this argument is not yet on solid footing.

Explosion mechanism: as an accreting white dwarf gets to Chandrasekhar mass the carbon begins to burn:

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow \begin{cases} ^{23}\mathrm{Mg} + n \\ ^{23}\mathrm{Na} + p \\ ^{20}\mathrm{Ne} + \alpha \end{cases} \tag{1}$$

Rate coefficient increases with temperature. At some point burning becomes runaway process, burns much of star to heavy elements (Si–Ni). Energy release disrupts star.

The light we see from the SN Ia is due to radioactive decay, primarily of ^{56}Ni, heating the remnant and being re-radiated as optical light:

$$\begin{aligned} {}^{56}\mathrm{Ni} + e^- &\rightarrow {}^{56}\mathrm{Co} + \nu_e \quad 6 \text{ days} \\ {}^{56}\mathrm{Co} + e^- &\rightarrow {}^{56}\mathrm{Fe} + \nu_e \quad 77 \text{ days} \end{aligned} \tag{2}$$

(These are mainly K-shell captures, followed by γ rays.)

Observational properties of SN Ia. Key characteristics:

- Spectrum dominated by singly-ionized metals. Si^+, S^+, Ca^+, Fe^+.
- Lines Doppler broadened to several $\times 10^3$ km/s.
- Luminosity rises to peak, then declines on timescale of a several weeks. Decline is slower at longer wavelengths; second maximum in I band (near infrared).

Typical peak absolute magnitude (magnitude viewed from 10 pc distance) is $M_V \sim -18$.

- $\sim 10^9$ times brighter than the Sun.
- Visible to naked eye down to $V = 6$ (hundreds of kpc).
- With modest size telescope, observable to cosmological distance, e.g. $V \sim 22$ at $z = 0.2$.

In order to use as a standard candle this must be uniform, but it's not, dispersion is ~ 0.6 magnitudes. This can be reduced using the *Phillips relation* (Phillips 1993 - ApJ 413,L105): the peak absolute magnitude correlates with how rapidly the SN fades:

$$M_V(\text{peak}) = -20.88 + 1.95\Delta m_{15}(B), \tag{3}$$

with scatter of 0.26 mag. Here $\Delta m_{15}(B)$ is the number of magnitudes the SN fades in 15 days after peak in the B (blue) waveband (rest-frame!). So longer-duration SNe Ia are brighter. Variants of this method reduce scatter to $0.15 - -0.2$ mag.

The absolute normalization of the SN Ia luminosity is not known, we can only measure relative distances to different redshifts. E.g. can get Ω_m and Ω_Λ, but not H_0.

Supernova survey strategies. Many steps are required in a SN survey.

Detection:

- A given patch of sky is surveyed repeatedly. Look for new objects.
- Often difficult because SN Ia is usually fainter than the host galaxy – need good image subtraction.

- Must match calibration, point spread function to "reference" image.

Classification: SNe II/Ib/Ic are much more common than Ia, and are not good standard candles. Must reject other types; Ic is especially hard. Options:

- Spectroscopic classification – find e.g. identifying Si^+ feature of Ia.
- Photometric classification – use relative brightnesses (colors!) in different wavebands, do χ^2 fit, Bayesian analysis, etc.
- Light curve – look for 2nd peak in near IR. (But need IR data → space observations.)

Redshift determination: (best is to have multiple techniques)

- Spectroscopic z of supernova – conceptually simplest but spectrum often of low signal/noise ratio.
- Photometric z of supernova – just like classification, find z that minimizes χ^2.
- Spectroscopic z of host galaxy – most precise method, since host lines are much narrower than SN (hundreds of km/s). But often fail to find and definitively identify a line in host spectrum.
- Photometric z of host galaxy – possible in principle, dangerous in practice because galaxy spectra are too diverse.

Magnitude (flux) determination:

- Must calibrate the detector – need watts, not "counts." Complicated because of atmospheric extinction, losses in optics, detector efficiency, etc.
- Correct for dust extinction in the Milky Way. ("Everyone" uses dust maps based on FIR 60–100 μm emission from dust, several calibrations of FIR → extinction relation.)
- Correct for dust extinction in the host galaxy. FIR of no help here – use observations of SN in multiple wavelengths to estimate reddening, then use extinction/reddening ratio based on our own Galaxy.

(These are all major sources of systematics, and may ultimately limit how well we can do with SNe Ia.)

What are the worries?

- Calibration of astronomical detectors is hard; a few percent is possible, $\sim 1\%$ might be achievable in the next few years with enormous effort. Remember one is comparing e.g. optical fluxes at low z to near IR at high z so must cross-calibrate against different wavelengths.
- Extinction/reddening ratio in host galaxy may vary. (Probably does!)

- Very large dust grains ($\gg \mu$m) with no smaller grains could cause extinction but no reddening; can mimic Λ if spread through intergalactic space. (But predicts wrong behavior of flux-redshift curve at $z > 1$.)

- Selection effects – do we preferentially see the brighter SNe at high z?

- Population of SNe Ia may be evolving – we don't understand residuals in Phillips relation, so maybe the SNe at high z are intrinsically fainter? E.g. from the Supernova Legacy Survey, Sullivan et al. (2006 - ApJ 648,868) find that SNe Ia in star-forming galaxies have slower decline and are brighter than those in non-star-forming galaxies. Worry that the residuals also correlate with galaxy properties, hence z.

Results from SNe Ia. The SNe Ia were the first technique to directly measure the acceleration of the universe. For low-z observations this is typically quoted in terms of the *deceleration parameter* q_0, defined by:

$$q_0 = -\left.\frac{a\ddot{a}}{\dot{a}^2}\right|_{a=1} = \frac{1}{2}\Omega_m - \Omega_\Lambda. \tag{4}$$

So $q_0 > 0$ corresponds to a decelerating universe, $q_0 < 0$ to accelerating. From this one can show that

$$H_0 D_L = z + \frac{1-q_0}{2}z^2 + O(z^3). \tag{5}$$

(Homework exercise!)

In 1998 two supernova teams found that the Universe was accelerating, each with ~ 50 SNe:

- High-z Supernova Search: Riess et al. 1998 (AJ 116, 1009). $q_0 = -1.0 \pm 0.4$.

- Supernova Cosmology Project: Perlmutter et al. 1999 (ApJ 517, 565). $0.8\Omega_m - 0.6\Omega_\Lambda = -0.2 \pm 0.1$.

(The SCP result is not quite a constraint on q_0 because of the higher-order terms z^3, etc.)

This result was obtained with only supernovae at $z \leq 1$, and most at ≤ 0.6. Individual determination of Ω_m and Ω_Λ requires going to higher redshift. This requires going to near IR wavelengths, and then one goes to space to avoid the bright atmospheric glow in near IR. Primary machine thus far at $z > 1$ has been the Hubble Space Telescope; ground-based telescopes working at optical wavelengths have provided most of the lower-redshift supernovae.

2 Measurements of Hubble constant

The leading measurement of the Hubble constant today comes from the HST Key Project (Freedman et al. 2001 ApJ 553, 47). We will also discuss a few other methods that have been used or are promising for the future.

HST Key Project. The basic idea in this measurement is to use Cepheid variable stars to measure distances to nearby galaxies (≤ 20 Mpc). Then use these galaxies to calibrate secondary luminosity standards that are used for more distant galaxies (> 20 Mpc). Second step is necessary for the Hubble flow ($v = HD$) to dominate over random velocities of galaxies (typically a few hundred km/s).

Cepheids are high-mass (typical $\sim 5M_\odot$), luminous (typical $\sim 10^3 L_\odot$) stars near the end of their lives that are unstable against radial pulsations with periods typically of a few days. The radial pulsations are linearly unstable due to the increase of opacity as the star is compressed and He^+ ionizes to He^{2+} (traps heat which causes positive work during the expanding part of the cycle). They are stabilized at the nonlinear level which prevents the star from disrupting.

Cepheids have a range of luminosities, so the first step is to calibrate period-luminosity relation for Cepheids. The HST Key Project did this against the Large Magellanic Cloud at distance 50 kpc. They find

$$\begin{aligned} M_V &= -2.76 \log_{10} \frac{P}{10\mathrm{d}} - 4.22, \\ M_I &= -2.96 \log_{10} \frac{P}{10\mathrm{d}} - 4.90. \end{aligned} \tag{6}$$

HST can see Cepheids out to 20 Mpc in spiral galaxies. (Cepheids not found or at least very rare in ellipticals; crowding a problem at large distances.) Must correct Cepheid magnitudes for extinction (using reddening of $V - I$ color), possibly metal abundance. Use to extend calibration to secondary standards:

- SN Ia. [$71 \pm 2 \pm 6$]
- Tully-Fisher relation (luminosity – rotation velocity for spiral galaxies). [$71 \pm 3 \pm 7$]
- Fundamental plane relation (radius – surface brightness – velocity dispersion for elliptical galaxies). No Cepheids in the elliptical itself so use a spiral in the same cluster. [$82 \pm 6 \pm 9$]
- Surface brightness fluctuations (SB fluctuation – SB in bulge). [$70 \pm 5 \pm 6$]
- SN II: expansion velocity from spectrum $\to$ radius(time), combine with temperature to get luminosity prediction. Calibrated with Cepheids although could in principle be calibrated from theory. [$72 \pm 9 \pm 7$]

(H_0 in km/s/Mpc given for each method; first error is statistical, second is systematic.)

The final HST Key Project result is

$$H_0 = 72 \pm 3 \pm 7 \text{ km/s/Mpc}. \tag{7}$$

Major systematics:

- LMC distance – everything hinges on this! But many methods.

- Random velocities on large scales?
- Crowding – separation of Cepheid luminosity from neighbors.
- Dependence of $L(P)$ relation on metal abundance.
- Calibration of HST/WFPC2 camera.

Water maser method. One would like to have an independent calibration of the secondary standards. A promising technique is the water maser method. This method makes use of water maser emission in disks around central black holes in external galaxies. Use 22.23505 GHz ($6_{16} \rightarrow 5_{23}$) transition of H_2O. We'll discuss the classic measurement of Herrnstein et al. 1999 (Nature 400, 539) to NGC4258.

The Doppler effect typically suppresses maser activity unless line-of-sight velocity gradient $dv_\parallel/dr \approx 0$. As a clump of matter rotates in the disk, this condition is met in two places:

- When $|v_\parallel|$ is maximized – high-velocity emission.
- When $v_\parallel = 0$ – systemic emission. In principle can be in front of or behind BH but only see in front of.

With very long baseline interferometry, can resolve the maser source (!) and measure positions θ for each emitting region. From Kepler's law:

$$v = \sqrt{\frac{GM}{D\theta}} \sin i_s, \tag{8}$$

where D=distance, θ=angle from black hole, M=mass of black hole, i_s =inclination. Observations of several maser spots give proportionality constant in $v \propto \theta^{-1/2}$. Case of NGC4258: θ ranges up to 9 mas, get $(M/D)\sin^2 i_s = 5.3M_\odot/\text{pc}$.

Now use systemic masers: make a scatter plot of $\theta, v_\parallel$, and the velocity gradient is

$$\frac{dv_\parallel}{d\theta} = D\frac{(GM)^{1/2}}{r^{3/2}} \sin i_s = \sqrt{\frac{GM}{D}\sin^2 i_s} \left(\frac{r}{D}\right)^{-3/2}, \tag{9}$$

where r is the distance from the BH to the masers. So we can find r/D. From position of systemic masers then get $i_s = 82°$, hence M/D.

To go further we need to break the mass-distance degeneracy. To do this, watch radial velocity and position of systemic masers move: get $\dot\theta$ and $\dot v_\parallel$. For NGC4258, measured $\dot\theta = 31.5 \pm 1\,\mu$as/yr, $\dot v_\parallel = 9.3 \pm 0.3\,$km/s/yr. Compare to theory:

$$\begin{aligned} \dot\theta &= \frac{1}{D}\sqrt{\frac{GM}{r}}. \\ \dot v_\parallel &= \frac{GM}{r^2}\sin i_s. \end{aligned} \tag{10}$$

Since r/D, M/D, and $\sin i_s$ are known, can pull out D given one or the other of these.

Herrnstein et al. quote a distance

$$D_{\rm NGC4258} = 7.2 \pm 0.5 \ {\rm Mpc}, \tag{11}$$

with the dominant uncertainty being the possibility of an eccentric disk. Consistent with HST Key Project, 8.0 Mpc±10%.

This is the best maser distance so far. With more masers one may establish independent Cepheid calibration (without LMC); or eventually even measure H_0 directly (requires more distant masers).