1.9. *Question 8*

QUESTION: Explain how Supernovae (SNe of Type Ia in particular) are used in the measurements of cosmological parameters.

This is adopted from my own qual notes.

Suppose a very bright standard candle exists throughout the history of the universe; since the luminosity of the candle is known, we would be able to use it to measure the luminosity distance (Eqn. 13, using $R = \frac{c}{H_0}\sqrt{|\Omega_\kappa|}$ and sinn to represent sin, sinh, etc.):

$$d_L = (1+z)\frac{c}{H_0}\frac{1}{\sqrt{|\Omega_\kappa|}}\mathrm{sinn}\left(\sqrt{|\Omega_\kappa|}H_0\int_0^z \frac{dz}{H}\right) \tag{34}$$

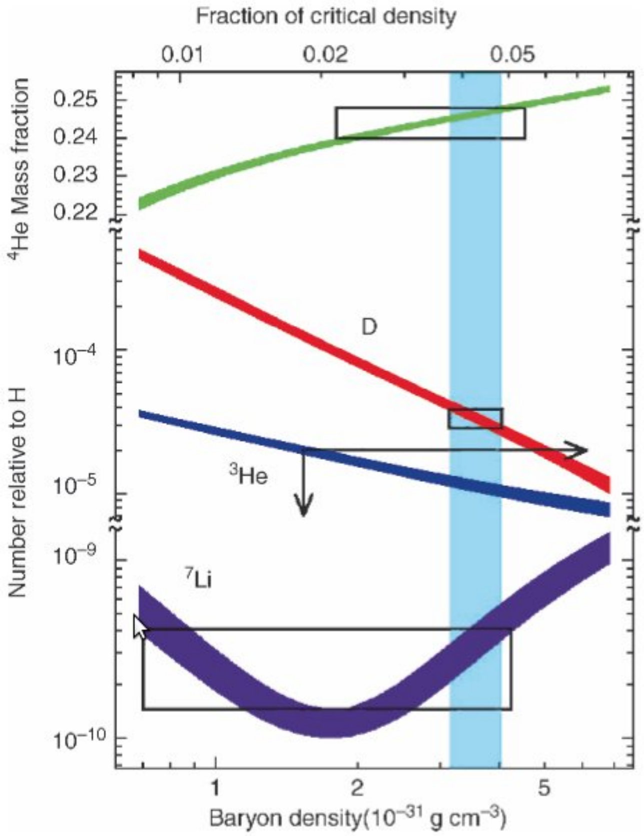

FIG. 12.— BBN predictions of the primordial abundances of light elements as a function of todays baryon density. If a photon density is known, then the x-axis scales with η. Rectangles indicate measured abundance values. Ω_b can be obtained by determining the baryon fraction consistent with measured abundances. From Schneider (2006), his Fig. 4.14.

This allows us to measure the expansion history of the universe.

As a (particularly appropriate) series of examples, let us consider the following. If the universe were empty, $\Omega_\kappa = -1$ and $H = H_0(1+z)$, giving us $d_L = (1+z)\frac{c}{H_0}\sinh\left(\frac{1}{H_0^2}\int_0^z \frac{dz}{1+z}\right)$. Assuming the universe is flat (Sec. 1.3), the luminosity distance reduces to

$$d_L = (1+z)d_c = (1+z)c\int_0^z \frac{dz}{H} \tag{35}$$

If $\Omega_\Lambda = 0$, then$\Omega_m = 1$, which gives $H = 2/3t = H_0(1+z)^{3/2}$. A critical matter-dominated universe has on average smaller d_L than an empty universe. If $\Omega_\Lambda = 1$, then $H = H_0$ and while the comoving distance is much smaller than the curvature radius, d_L will be larger than either the empty or the critical matter-dominated universe.

SNe Ia are standardizable candles: they have a maximum luminosity spread of $\sigma \approx 0.4$ mag in B-band, which is empirically correlated with the rise and decay times of the light curve. This "Phillips Relation" allows for the determination of the true peak absolute magnitude of any SN Ia. (It should be noted that colour is almost just as important as duration; see below.) Since redshift can easily be determined from SNe Ia spectra (Si II P Cygni profile, intermediate element absorption lines, etc.), and SNe Ia are visible out to enormous distances, a plot of luminosity distance vs. redshift, or luminosity distance modulus vs. redshift covering a large portion of the universe's history is feasible.

Fig. 13 shows the result, from Riess et al. (2004). The results strongly rule out the empty and critical universes discussed earlier, in favour of a universe with a non-zero Ω_Λ. These results are in agreement with the ΛCDM concordance cosmology values $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$.

1.9.1. *Describe systematic errors.*

The two common methods used to determine the luminosity distance moduli to SNe are the stretch and multi-light curve method (MLCS). The stretch method fits a dataset of SNe Ia to a "stretch parameter" α (which adjusts the light curve based on the fall-off timescale equivalent to δm_{15}) and a luminosity/colour slope β. The MLCS method uses a low-z set of SNe to determine the Phillips and colour relations, and then uses these values for high-z SNe. MLCS also treats intrinsic SNe reddening with extinction from the galaxy independently. Both features can add systematics into the analysis. The two methods, however, give remarkably similar results.

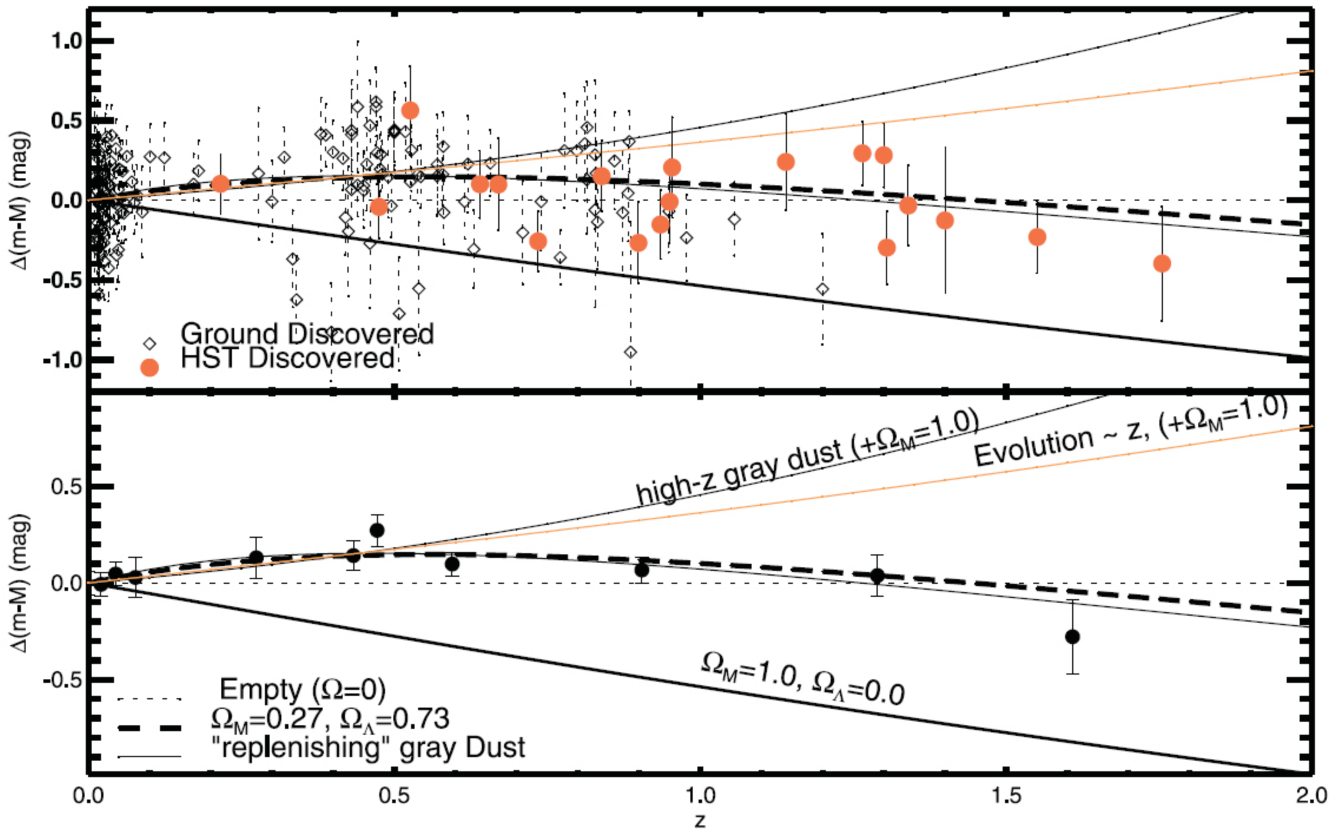

FIG. 13.— Above: the difference in luminosity distance modulus (positive means more distant, since $\Delta(m - M) = 5\log(d_L/10\,\mathrm{pc})$) between observed values from SNe Ia and theoretical values in an empty universe, as a function of redshift. Various cosmological scenarios are also depicted. Below: the same data, except averaged in redshift bins for a cleaner fit. A best fit $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ is also drawn. Note that at lower z the observed deviation is positive, indicating a greater luminosity distance (equivalent to reduced flux) than expected for an empty universe. Making Ω_m non-zero only increases $E(z)$ which decreases the luminosity distance, so this increase must be accounted for by a non-zero Ω_Λ. At large z the curve approaches the same slope as the $\Omega_m = 1$ line, indicating matter dominance in the early universe. The "grey dust" lines are for a uniform extinction medium (dust that provides dimming without reddening) - the "replenishing grey dust" assumes a constant dust density even though the universe is expanding. The orange line assumes SNe Ia become dimmer by a percentage monotonically increasing with z (i.e. early universe SNe Ia are much dimmer than modern-day SNe Ia). From Riess et al. (2004), their Fig. 7.

There are a large number of systematic errors. They include:

1. Calibration: k-corrections require good knowledge of both the SED of a typical SN Ia as well as the filter system used.
2. UV spread: SNe Ia have a higher spread in the UV than in optical or infrared (in the IR SNe Ia actually have an uncalibrated σ of 0.15!), which becomes problematic when redshift pulls the U band into the B band.
3. Reddening: intrinsic reddening of the SNe themselves and reddening due to dust should be handled separately, but in practice they are hard to deconvolve. Intrinsically fainter SNe Ia are redder than normal Ias, an effect almost as important as the luminosity/falloff time relationship, but the same effect occurs with dust extinction.
4. Galactic evolution: fainter SNe Ia tend to be embedded in older stellar populations. This translates to a $\sim 12\%$ brightness increase for $z = 1$ SNe Ia due to increased star formation. While this is not a problem if the stretch factor corrects for light curves, it turns out that current fitting methods do not bring SNe Ia in high and low-mass galaxies to the same absolute magnitude (the difference is ~ 0.08 mag).
5. Since the progenitors of SNe Ia are unknown, it is not known if the physical nature of SNe Ia changes with redshift.

1.9.2. *Describe alternate explanations to the SNe luminosity distance data, and why they can be ruled out?*

Alternate scenarios for why the luminosity distance appears to increase for mid-z values include a 20% drop in SNe flux due to a "grey dust" (uniform opacity dust). This does not work, since at higher redshift the obscuration would be more significant, and this trend is not seen in the dataset. The idea that SNe Ia have fundamentally changed from the young universe to today is also difficult to support: the measured luminosity distance approaches what we would expect for a critical matter dominated universe at high redshift (a consequence of Λ becoming prominent only recently). It is not obvious how a change in the nature of SNe Ia could produce the same trend.

1.9.3. *Can SNe II be used as standard candles?*

Yes; in particular the recombination bump of SNe II-P can be used as a standardizable candle (Kasen & Woosley 2009). In these SNe, there is a tight relationship between luminosity and expansion velocity (as measured from ∼5000 ÅFe II absorption lines), explained by the simple behavior of hydrogen recombination in the supernova envelope (Kasen & Woosley 2009). There is sensitivity to progenitor metallicity and mass that could lead to systematic errors, and overall SNe II are dimmer than SNe Ia, however (Kasen & Woosley 2009).