

These questions were motivated by reading the article "Is There Evidence for a Hubble Bubble? The Nature of Type Ia Supernova Colors and Dust in External Galaxies" by Conely et al. Many of these questions are not related to specifics in this article, however, so you may not want to spend a large amount of time reading the article very closely.

I would expect a grade of around 75% would be required to pass this cume.

1. (25 points) Cosmology

- (a) (5) What is the observational definition of the Hubble constant?

When you measure recession velocities of galaxies, you find that the velocity is proportional to the distance:

$$H_0 \equiv v/D$$

- (b) (5) What are the units of the Hubble constant, and what is the currently accepted value? What does the value $1/H_0$ relate to?

Units are km/s/Mpc, and current accepted value is about 70. $1/H_0$ is a timescale for the expansion: the age of the Universe if expansion rate has been constant (which it hasn't, and wouldn't be expected).

- (c) (5) What is a "peculiar velocity field"? What are typical amplitudes of peculiar velocities? What is the peculiar velocity of the Milky Way, and how is it measured?

Galaxies move with respect to a uniformly expanding frame. These motions are called peculiar velocities. Typical values are several hundred km/s. For the Milky Way, the peculiar velocity is around 600 km/s as inferred from the dipole in the cosmic microwave background.

- (d) (5) What is the theoretical definition of the Hubble constant, i.e. what is its formulation in terms of cosmological parameters? Is it expected to vary with time, and if so, how?

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc}{a^2} + \Lambda$$

$$H^2 = H_0^2 \left(\frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2} + \Omega_\Lambda \right)$$

- (e) (5) What are the cosmological parameters currently thought to be important for characterizing the expansion of the Universe? What are currently accepted values/ranges for these parameters?

Current important parameters: $H_0 \sim 70$, $\Omega_m \sim 0.3$, $\Omega_b \sim 0.04$, $\Omega_\Lambda \sim 0.7$, $w \sim -1$.

2. (30 points) Extinction

- (a) (5) What does $E(B - V)$ mean, quantitatively?

$E(B - V)$ is the color excess, $A_B - A_V$.

$$E(B - V) = -2.5 \log \frac{(F_B/F_V)_{\text{reddened}}}{(F_B/F_V)_{\text{unreddened}}}$$

- (b) (5) What is the definition of R_V ? Why is $R_B = R_V + 1 \approx 4$?

$$R_V = \frac{A_V}{E(B - V)}$$

$$R_B = \frac{A_B}{E(B - V)} = \frac{A_V + E(B - V)}{E(B - V)} = R_V + 1$$

R_V is measured to be about 3.1 in the Milky Way, so $R_B \approx 4$

- (c) (10) What is meant by an extinction law? Make a sketch of the typical Milky Way extinction law. Make sure the label the axes properly, and describe the behavior of the curve that you sketch.

An extinction law gives the wavelength dependence of extinction by interstellar dust. Plot should give something like $A(\lambda)/A(V)$ vs wavelength, and should show increasing extinction toward shorter wavelengths with approximately correct slope, ideally also the 2200 Å bump. Plot should have appropriate numbers on axes.

- (d) (5) Describe qualitatively how an extinction law with $R_V \sim 1$ would differ from the standard extinction law. For example, imagine you looked at two identical stars through two different dust clouds that had different values of R_V . How would your observed quantities differ?

With $R_V \sim 1$, the color dependence is significantly greater, i.e. a bigger color change at fixed A_V .

- (e) (5) How would you go about measuring an extinction law?

Observe objects with well-known (or calculatable) SED, e.g. hot stars through various sight lines.

3. (30 points) Type Ia Supernovae

- (a) (5) What is the observational distinction of Type I and Type II supernovae?

Type I SN don't show H lines, Type II do.

- (b) (5) What are thought to be the physical scenarios that give rise to the different types of supernovae?

Type II supernovae (and Ib and Ic) arise from massive star collapse. Type Ia arise in binary system where mass transfer pushes one component over Chandrasekar mass.

- (c) (5) Explain why Type Ia supernovae are of interest to cosmology.

They can be used as standard candles (see next question), and they are intrinsically bright so they can be seen to large distances. As such, you can measure the distance- redshift relation, which depends on cosmological parameters.

- (d) (5) What is meant by the width-luminosity relation? Make a sketch (label the axes!) to demonstrate this.

The shape of the light curve is related to the peak luminosity. Slower decliners reach a bright peak luminosity. Plot should show SN Ia's peaking somewhere around $M_V \sim -18$, and should show a couple of curves with peak luminosity depending on light curve width.

- (e) (5) Describe the characteristics of the observations of Type Ia supernovae that suggest that the expansion of the Universe is accelerating.

Type Ia supernovae at higher redshift appear fainter than expected in a non-accelerating universe.

- (f) (5) What are some of the possible caveats that people have discussed about the use of type Ia supernovae? What arguments have been used to address some of these concerns? Why do people care about understanding the nature of the progenitors of type Ia supernovae?

Grey dust, and evolution. Dust is very unlikely because of observations of $z > 1$ supernovae, which probe far enough back to show deceleration. Evolution is a trickier question: people have looked at colors and rise times. Understanding progenitors would definitely help to address evolution issues.