1 Flux

Comoving stars radiating at constant luminosity $L$ and distributed homogenously throughout the universe (with a FRW metric) are lit at time $t_0$. What is the flux measured by a comoving observer at time $t_1$? Write the answer in terms of the function $a(t)$ and the density of stars at time $t_1$. Calculate in two ways:

1. Sum up the contribution of the fluxes of the stars from which light had enough time to arrive.

2. Write an equation for the local energy density in the emitted photons and integrate it from $t_0$ to $t$.
   
   Does the result depend on the value of the spatial curvature $k$?
   
   For $a(t) \propto t^\alpha$, what is the condition $\alpha$ has to satisfy so that the result will not diverge for $t_0 \to 0$.

2 Hubble’s Constant and dark energy

A reminder – The distance modulus, $\mu_0 = m - M$, is the difference between the apparent magnitude, $m$, and the absolute magnitude, $M$, of an astronomical object, and is given by:

$$\mu_0 = 2.5 \log\left(\frac{L}{4\pi F \times (10 \text{ pc})^2}\right),$$

where $L$ is the intrinsic luminosity of the object and $F$ is the observed flux.

1. Hubble’s Constant from Type Ia supernova (phenomenological) light curves

In the attached file¹, you are given data of the measured luminosity distance of different type Ia supernovae, along with their measured redshift. The format of the data is either $(z, \mu_0)$ for large redshifts, or $\log(c[km/s]z), \mu_0$ for small redshifts. The intrinsic luminosities of the supernovae are different, but they can be reliably estimated from the observational Phillips relation together with nearby type Ia supernovae with known distances (e.g., if their host galaxies include cepheids). The detection that the Universe is accelerating was based on this data set.

¹Taken from http://iopscience.iop.org/article/10.1086/300499/pdf
Consider the following subsample of supernovae from the low z sample.

<table>
<thead>
<tr>
<th>Name</th>
<th>Host galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN1990af</td>
<td>2MASX J21345926-6244143</td>
</tr>
<tr>
<td>SN1992ag</td>
<td>ESO 508- G 067</td>
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<tr>
<td>SN1992bg</td>
<td>2MASX J07415700-6231144</td>
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<tr>
<td>SN1992bo</td>
<td>ESO 352- G 057</td>
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<tr>
<td>SN1992bs</td>
<td>FCCB 0602</td>
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<td>SN1993ag</td>
<td>2MASX J10033546-3527410</td>
</tr>
<tr>
<td>SN1994M</td>
<td>NGC 4493</td>
</tr>
<tr>
<td>SN1994T</td>
<td>CGCG 016-058</td>
</tr>
<tr>
<td>SN1995ac</td>
<td>2MFGC 17122</td>
</tr>
</tbody>
</table>

(a) Determine the redshift for each host galaxy through their spectrum. The most important absorption lines are Mg (5175.3 Å), Na (5894.0 Å), and the most important emission lines are Hβ (4861.3 Å), [OIII] (4959.0 Å, 5006.8 Å), Hα (6562.8 Å).

(b) Provide a rough upper limit to the peculiar velocities of galaxies, based on your determined redshifts.

(c) Use the given μ0 for these supernovae to determine Hubble’s constant. Present your result graphically.

(d) What controls the error of your result (you can assume that typical peculiar velocities of galaxies are hundreds of km/s)?

(e) Can you infer more cosmological parameters from these supernovae?

2. Hubble’s Constant from GW170817 (basic physics) gravity waves

On August 17, 2017 the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral, GW170817. From the observed ~ 3000 cycles of the binary, the luminosity distance to the source was determined to be 40^{+8}_{-14} Mpc (90% credible intervals). An electromagnetic follow-up campaign identified a counterpart near the galaxy NGC 4993, consistent with the localization and distance inferred from the gravitational-wave data.

(a) Use the spectrum of NGC 4993 to determine the redshift of the galaxy.

(b) Assume that GW170817 coincides with NGC 4993, and determine Hubble’s constant.

(c) What controls the error of your result?

3. Accelerating Universe from high z Type Ia supernova light curves

Now use the full sample of supernovae (both low and high z).

(a) The redshift for the high z sample can be determined directly from identified lines in the supernova spectrum (a host galaxy is not required). Provide the physical reason that such a determination is possible for the high z sample but impossible for the low z sample.

(b) Which of the following cosmological models provides the best fit to the data? Present your result graphically (use log plot when appropriate).

\(^2\)can be retrieved from NASA/IPAC Extragalactic Database.
(c) Does the approximation \( d_L(z) \approx c/H_0[z + (1 - q_0)z^2/2] \) is accurate enough to determine the cosmological model? Present your result graphically.

(d) Assume that there is a systematic error in the use of cepheids as distance indicators, such that all supernovae luminosity distances are scaled by some constant factor. How would your results for \( H_0 \) and for the cosmological model change?

(e) Do you believe that the universe is accelerating?

Use the following cosmological models:

(a) \( \Omega_M = 1 \)

(b) \( \Omega_M = 0.3, \Omega_K = 0.7 \)

(c) \( \Omega_M = 0.3, \Omega_\Lambda = 0.7 \)