Calculating the redshifts of galaxies using spectroscopy and the Hydrogen-α (Hα) line

Updated December 2022 by A.S.A.

Background

Due to the expansion of the Universe, the wavelength of the light we observe coming from distant galaxies appears to be redshifted similarly to what we observe when an object is moving away with respect to us. This finding led astronomers V. Slipher and E. Hubble to propose a model where the Universe is expanding, in agreement with theoretical models by A. Eddington, G. Lemaître and W. de Sitter, among others.

The **cosmological redshift**, z, is the difference between the wavelength at which we observe a spectral line from a moving galaxy (λ_{obs}) with respect to the wavelength at which we observe the same spectral transition in the lab (λ_{lab}) , normalized to the value of the lab wavelength

$$z = \frac{\lambda_{obs} - \lambda_{lab}}{\lambda_{lab}} = \frac{\lambda_{obs}}{\lambda_{lab}} - 1. \tag{1}$$

For nearby galaxies, the redshift is related to the velocity at which the galaxy appears to be moving away from us (in fact, this velocity is not how the galaxy travels, but how the space is expanding), v, through the velocity of light (c)

$$v = cz. \tag{2}$$

Although distant galaxies are all moving away with respect to us (redshifted), some of our local neighbours, such as the Andromeda galaxy, are moving towards us (blueshifted) and then appear to have negative redshifts. In fact, the Andromeda galaxy and the Milky Way are attracting each other gravitationally, and they will collide in some 4.5 billion years from now. Then, after an astronomically brief time of enhanced star formation, the two galaxies will merge and become an old elliptical galaxy that won't form many new stars any longer.

Since the Universe is expanding, the more distant galaxies appear to be moving away faster than the closer ones and this relation between their velocities and distances can be used to estimate the distance of a galaxy knowing the expansion rate of the local Universe. The expansion rate of the Universe is given by the **Hubble's constant** H_0 = 74 (km/s)/Mpc[1], and thus the distance (d) to a galaxy with redshift z and velocity v is given by

$$d = cz/H_0. \tag{3}$$

When considering further away galaxies, the fact that Hubble's constant vary with time needs to be taken into account. We can now use this law to estimate the distance to several galaxies and compare them to the distance to the Andromeda galaxy (0.778 Mpc).

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1 Mpc = Mega Parsec = 3.086 x 10^{22} m

Procedure

The Appendix contains spectra for several galaxies at short and intermediate-distances. For the spectrum of each galaxy, determine approximately the wavelength at which the Hα line is observed (λ_{obs}). Knowing that the laboratory wavelength for Hα is 6563 Å, use (1) to estimate the redshift, (2) to calculate the velocity of your galaxy, and (3) to estimate the distance in Mpc.

A step further: Investigating the expansion of the Universe

If you want to apply the above relations to more distant galaxies, we will be travelling to a time when the Universe may be quite different to what it is now. This difference also affects the way the Universe was expanding and thus Hubble's constant.

We can't use any longer the simple linear Hubble's law, but we will need to include the detailed expansion models. Although at low redshifts (for the near Universe) all models are very similar to the linear Hubble's law, as we look into the more ancient Universe, depending on the amount of baryonic (normal) matter, dark matter, and dark energy (which affects the expansion ratio) of the model, the relation between distance and redshift will vary accordingly (see figure 1). This is why independent determinations of the distance of objects are so important in Cosmology to understand the structure, the past, and the fate of the Universe.

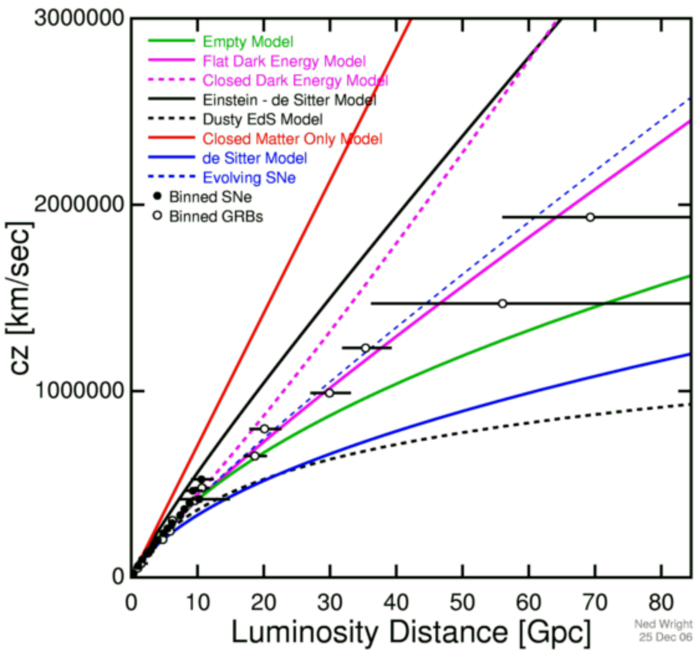


Fig 1. Redshift vs distance for various cosmological models. The observational data from Supernovae Ia (SNIa) and Gamma Ray Bursts (GRB) are also included for comparison. Credit: UCLA Cosmology [3].

To think about

- We nowadays have detected very distant, active galaxies (known as quasars) down to redshift z=6. What would be their recession velocity if we use formula (2)? Do you find anything "odd" there? Note that because the "velocity" associated to redshift is not a physical velocity (an object moving through space) but **the velocity at which space itself expands**, a superluminic velocity is not a conceptual problem here.
- The more distant the galaxy is, the more redshifted the Hα line will be... until it is not seen by our optical spectroscope any more. **How can we classify more distant galaxies?**
- **How do you think one can get an absolute distance for a very distant object?** Hint: How far a light you see in the distance is will depend on whether the light is a torch or the front light of an airplane. Have you heard about Cepheids or Supernova SN Ia?

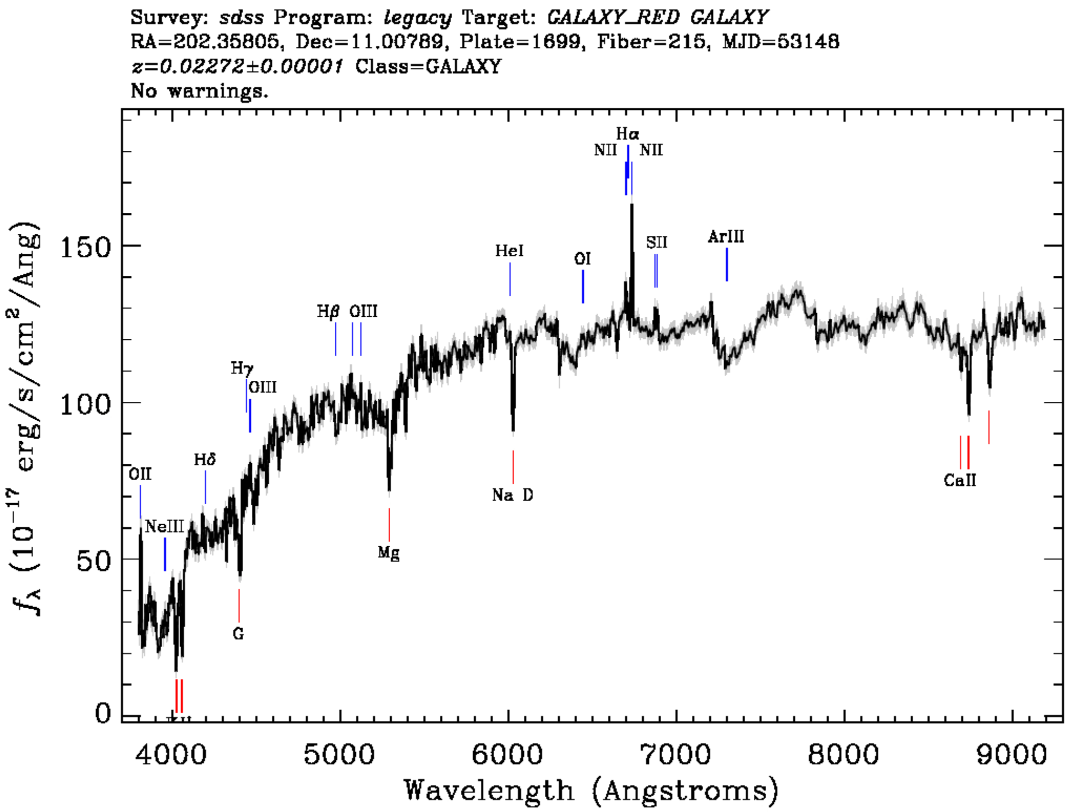
Learn more

[1] "Introduction to Astronomy and Cosmology", Ian Morison, 2008, Ed. John Wiley & Sons Ltd.
[2] Sloan Digital Sky Survey Galactic Redshift activity: https://skyserver.sdss.org/dr12/en/proj/advanced/hubble/redshifts.aspx#ex15
[3] UCLA Cosmology, E.L. Wright: http://www.astro.ucla.edu/~wright/old_new_cosmo.html

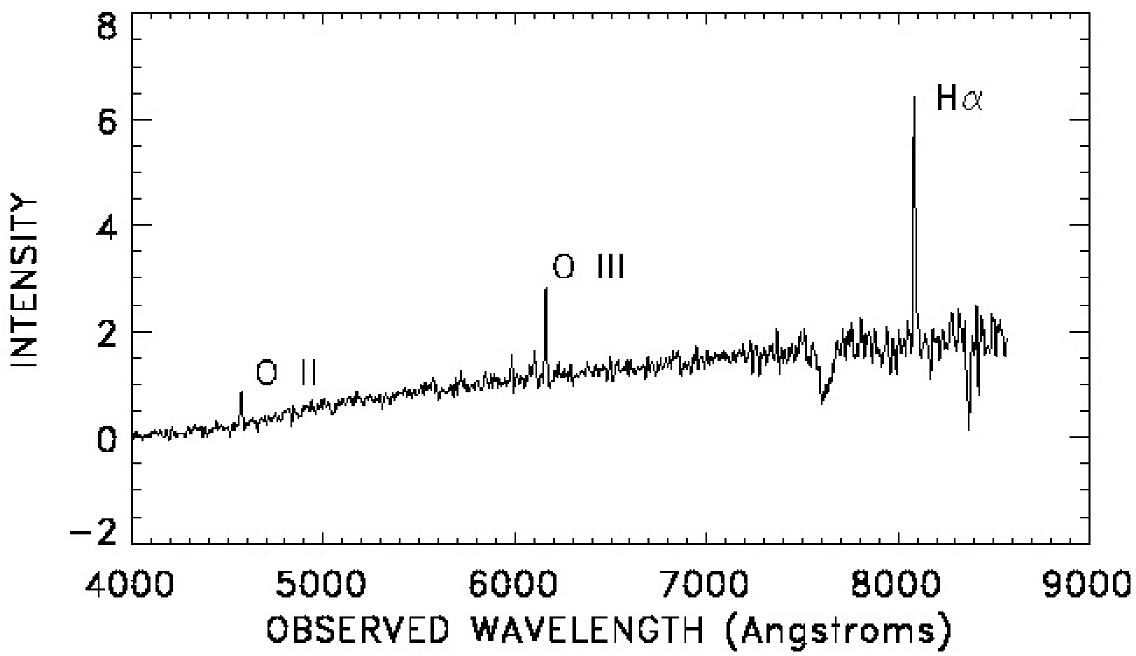
Appendix

Below you can find a small sample of galaxies to measure. More of them can be found in the above reference of the Sloan Digital Sky Survey.

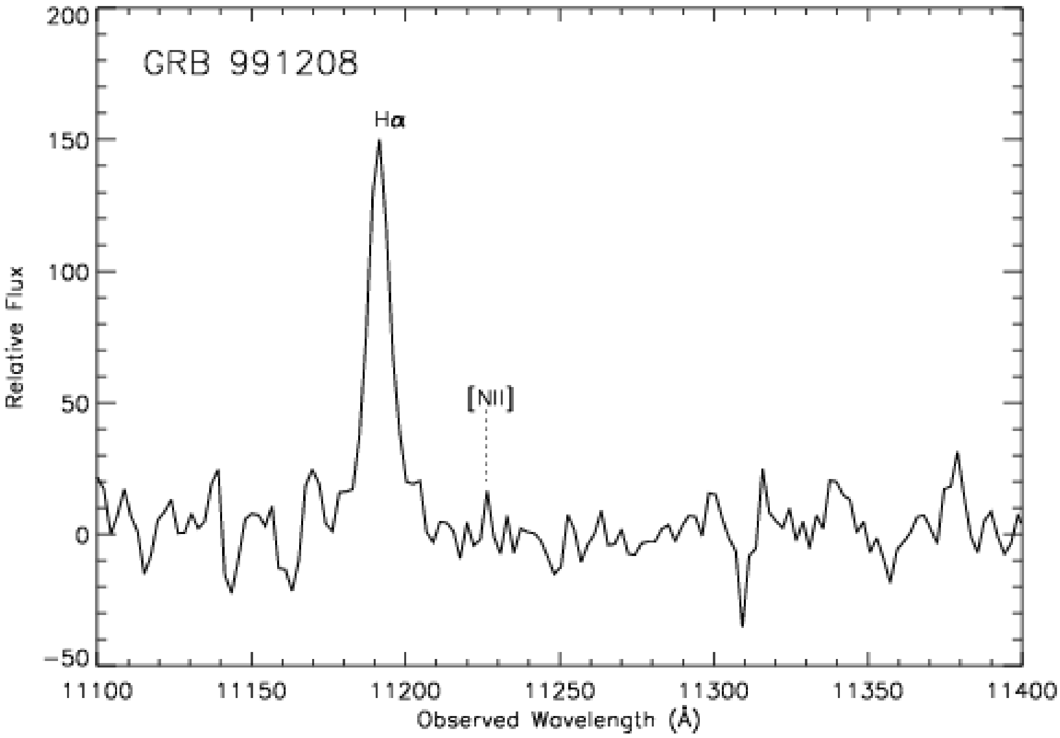
1. A red galaxy from the Sloan Digital Sky Survey (www.sdss.org):



2. A galaxy from the Hubble Deep Field (www.ifa.hawaii.edu)



3. A galaxy that originated a gamma ray burst (Levesque et al., 2010, AJ 140, 1557):



4. Spectrum of the Quasar 3C273 (Yates et al. 1989, MNRAS, 241, 167):

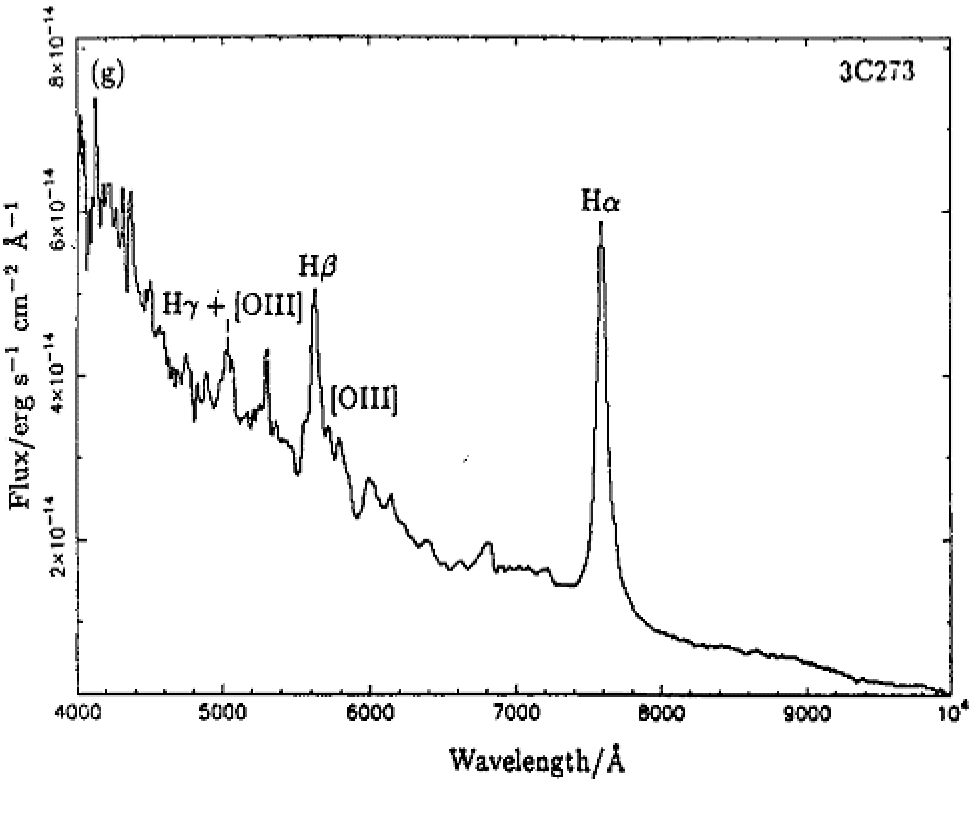


Table to record your results:

Galaxy	**Hα wavelength (Å)**	**Redshift**	**cz (km/s)**	**Distance (Mpc)**	**Comments**