Spectral Lines and Redshifts

an exercise for the cosmology course

Andreas Andersson

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Introduction

Almost all astronomers today believe that the universe is expanding. This is a belief based on observational facts. In 1931, Hubble and Humason published their classical paper (Hubble, Humason (1931), ApJ 74,43) where they compared the redshifts and distances of remote galaxies, and determined a velocity-distance relation (now called the Hubble law). They found $H_0 = 560$ km/s/Mpc. This result has been revised several times, but the value of H_0 is still uncertain. The currently favoured value is $H_0 \sim 75$ km/s/Mpc.

Definitions

Assume that we observe a spectral line at wavelength λ, and that this line has the rest wavelength λ_0. By definition, the redshift is then

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\lambda}{\lambda_0} - 1 \tag{1}$$

which can be rewritten as

$$\frac{\lambda}{\lambda_0} = z + 1 \tag{2}$$

Eq. 2 shows that the ratio between the observed and the emitted wavelength is constant for all lines with the same redshift.

For two lines with the same redshift, and with rest wavelengths λ_{01} and λ_{02}, there is then a relation

$$\frac{\lambda_1}{\lambda_2} = \frac{\lambda_{01}}{\lambda_{02}} \tag{3}$$

Eq. 3 is valid even if, for example, λ_1 is in the optical while λ_2 is in the radio band, and this equation can be used to identify the lines.

Scheme for determining the redshift

a Observation of the spectrum

b The wavelengths for all lines are measured

c The lines are identified with known spectral lines

d The redshift z is calculated for each line

e The average value of z is calculated (and the error of this average value)

f The distance to the object is calculated

Comments about this scheme

a,b Along with the spectrum of the object, a comparison spectrum with lines of known wavelengths is observed. This comparison spectrum is then used to calibrate the spectrum of the object. In this exercise, a) and b) have already been done.

c To make the identification of the lines easier, there are tables over the expected lines from a quasar or a distant galaxy. Which lines are observed in which object is dependent on, at one hand the redshift of the object and the observed wavelength range, on the other hand the nature of the object itself. For instance, quasars have much more emission lines than ordinary galaxies. In table 4, expected emission lines are listed. Among the emission lines are several forbidden transitions. These are transitions which have so low probability of spontaneous de-excitation that they are never seen in the laboratory (in laboratory conditions, the time scale of collisional de- excitation is much shorter than in the rarefied gas found in space). In table 5 are listed some important absorption lines. These lines are often strong transitions to the ground energy level.

When trying to identify lines, one can choose a pair of strong lines and, using Eq 3, test against strong pair of lines in the tables. When Eq. 3 is satisfied by a pair of lines, the redshift z can be computed and used to calculate the rest wavelengths λ_0 for other lines. These values are then compared with λ_0 for known lines in the tables, until all the lines have been identified. In the spectra of some objects one has found several systems of lines with somewhat different redshifts z. One must then identify the lines in each system separately. Quasars with both emission and absorption lines do usually have one value z_{em} for the emission, and another (or several others) value z_{abs} for the absorption. Usually $z_{em} > z_{abs}$ but sometimes z_{abs} is slightly larger than z_{em}, in spite of the fact that the absorption must occur in front of the strong radiation source.

There is a widespread belief that the absorption occurs in gas which have been thrown out of the quasar by the strong radiation pressure. A large fraction of the radiation energy is in the strong emission lines. One believes that this can give rise to a "locking" between the relative velocities of the "clouds", if a certain strong spectral line coincides with an absorption line in another gas cloud.

d When the lines are identified, a redshift z can be computed for every line

e The average value of z is computed for each system. The error in this average should also be calculated.

f Calculate the proper distance to the object for a matter dominated universe (in Mpc). For extra credit: calculate the proper distance to the object for a more realistic cosmology (in Mpc).

Observed spectra

Three objects A, B and C have been observed.

Object A

From the apparently faint galaxy A was obtained a spectrum, which was well defined in the range 6000-7000 Å. A blended emission line, often found in galaxies, was seen at 6100 Å, and two absorption lines at 6442 and 6469 Å. In a previous spectrum, at longer wavelengths, a strong emission line was detected at 10740 Å. The galaxy A is known as a radio source, and can be assumed to be intrinsically luminous and therefore distant. Determine the redshift ($z_{em} = z_{abs}$) and the proper distance.

Object B

The spectrum of the blue object B has been examined. One found two strong (broad) emission lines, which defines a redshift z_{em}. Furthermore, two systems of (narrow) absorption lines were found. The following wavelengths were measured:

Table 1: Emission and absorption lines in source B.

In emission	3496 Åand 4466 Å	
In absorption	3448.5 Å	strong
	3514.1 Å	weak
	3520.1 Å	strong
	3588.6 Å	medium strength
	3865.2 Å	weak
	4033.0 Å	weak
	4392.0 Å	rather strong
	4398.3 Å	rather strong
	4482.7 Å	rather strong
	4489.3 Å	rather strong

Identify the lines. The lines seen in emission are also seen in absorption in both systems. Calculate individual values of z_{em}, z_{1abs} and z_{2abs} for the lines, and averages (with errors) and corresponding proper distances for each system. Discuss the results.

Object C

In a spectrum of the quasar C one found four emission lines and a large number of absorption lines. The wavelengths of the emission lines were:

Table 2: Emission lines in quasar C.

In emission	3597 Å	strong
	4577 Å	strong
	4835 Å	weak
	5640 Å	fairly strong

The wavelengths of the absorption lines are listed in table 3. Identify the lines and determine z_{em}. You should find that the absorption lines will be divided into two systems. Identify the lines and determine the redshifts and proper distances as in B. Compute distances to all the objects using the Hubble law. Discuss the results.

Table 3: Absorption lines in quasar C.

In absorption	3580.6 Å	strong	3936.2 Å	
	3586.6 Å	strong	4104.9 Å	
	3648.5 Å		4111.5 Å	
	3653.9 Å		4131.7 Å	
	3660.0 Å		4137.9 Å	
	3664.1 Å	weak!	4496.1 Å	
	3712.5 Å		4517.4 Å	
	3715.9 Å		4559.9 Å	very strong
	3725.0 Å		4567.2 Å	blend, very strong
	3729.0 Å		4573.4 Å	very strong
	3933.1 Å	blend		

Table 4: Some *emission* lines which have been observed in quasars or galaxies.

Identification	λ_0 (Å)	Remarks
Lyα	1216	Strong, broad
N V	1249	blend of 1238.8 & 1242.8
C IV	1549	blend of 1548.2 & 1550.8, strong
[C III]	1909	fairly strong
Mg II	2798	blend of 2795.5 & 2802.7, strong
[O II]	3727	Blend of 3726.0 & 3728.2, Often found in galaxies
Hγ	4340	
[O III]	4363	
Hβ	4861	strong
[O III]	4959	
[O III]	5007	sometimes very strong
Hα	6563	strong

Table 5: *Absorption* lines in certain quasar or galaxy spectra.

Identification	λ_0 (Å)	Remarks
Lines from absorption in thin gases		
Lyα	1215.7	Strong! Often found in QSO's with large z.
N V	1238.8	
N V	1242.8	
Si II	1260.4	
Si II	1264.7	
Si II	1265.0	
C II	1334.5	In certain cases 1334.5 is blended with 1335.7 to a wavelength of 1335.3 Å.
C II	1335.7	
Si IV	1393.8	
Si IV	1402.8	
Si II	1526.7	
Si II	1533.5	
C IV	1548.2	strong!
C IV	1550.8	strong!
Lines from absorption in late type stars		
Ca II K	3933.7	
Ca II H	3968.7	