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The ESO Slice Project (ESP) galaxy redshift survey*

IV. A discussion of systematic biases in galaxy redshift determinations

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Abstract. We present a detailed discussion of the redshift errors associated to the ESO Slice Project measurements. For a subsample of 742 galaxies with redshifts determined both from the absorption lines (V_{abs}) and from the emission lines (V_{emi}), we find an average difference $< V_{abs} - V_{emi} > \simeq +100$ km/s. We find that a similar effect is present in another, deeper redshift survey, the Durham/Anglo-Australian Telescope faint galaxy redshift survey (Broadhurst et al. 1988), while is absent in surveys at brighter magnitude limits. We have investigated in detail many possible sources of such a discrepancy, and we can exclude possible zero-point shifts or calibration problems. We have detected and measured systematic velocity differences produced by the different templates used in the cross-correlation. We conclude that such differences can in principle explain the effect, but in this case the non-trivial implication would be that the best-fitting template does not necessarily give the best velocity estimate. As we do not have any *a priori* reason to select a template different from the best-fitting one, we did not apply any correction to the ESO Slice Project velocities. However, as for a small number of galaxies the effect is so large that it is likely to have a physical explanation, we have also taken into account the possibility that the discrepancy can be partly real: in this case, it might help to understand the role of gas outflows in the process of galaxy evolution. In view of the future large spectroscopic surveys, we stress the importance of using different templates and making them publicly available, in order to assess the amplitude of systematic effects, and to allow a direct comparison of different catalogues.

Key words: surveys - galaxies: distances and redshift - galaxies: kinematics and dynamics

1. Introduction

The understanding of the formation, evolution and present properties of the large-scale structure of the Universe is a key problem in modern cosmology (see Peebles 1980, 1993). One of the most important results of the first redshift surveys was the previously unexpected existence of coherent structures and voids at very large scales. Explaining these structures was a challenge for popular models of galaxy formation, but at the same time represented a problem for the interpretation of results obtained on small volumes which could not be representative of the Universe. Therefore, the need of a "fair sample" of the Universe, in order to understand the process of galaxy formation and evolution, led to an increasing number of deeper redshift surveys. Redshift surveys are now an "industry" with its own standards. Reduction of an ever growing number of data is based on software packages specially developed to this aim. The redshift $z = \Delta\lambda/\lambda$, or, less rigorously, the "recession velocity" $V = cz$, is commonly determined using the wavelength shift of either absorption or emission lines appearing in the optical spectrum of a galaxy. Following the paper by Tonry & Davis (1979), most redshifts based on absorption lines are now obtained by cross-correlating galaxy spectra with one or more (or an average

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Correspondence to: cappi@astbo3.bo.astro.it of) "template" spectra, while redshifts based on emission lines are measured by fitting the individual emission lines. Moreover, emission and absorption lines are produced in different environments. In normal galaxies, the former (such as the [OII]$\lambda3727$ line) are generated in HII regions associated with recent star-formation, while the latter (such as the calcium Ca II K and H) are produced in stellar atmospheres and are related to the bulk of the star population. As a consequence, emission and absorption redshifts are not required to be exactly the same.

Despite the growing number of galaxy redshifts in the literature, most catalogues quote only the "best" estimate of the velocity of a galaxy, and take for granted the implicit and widespread assumption that, while for a given galaxy the absorption velocity V_{abs} and the emission velocity V_{emi} may differ, the average difference should be consistent with zero.

In the analysis of the ESO Slice Project (ESP; Vettolani et al. 1997; Zucca et al. 1997; Vettolani et al. 1998), we have devoted a particular effort to check the quality of our data, and in particular the precision of our absorption and emission redshift measurements which, as we have soon realized, present a puzzling discrepancy. Looking at the past and recent literature, we have also realized that this problem was not new, but was never discussed in a satisfactory way. We have therefore decided to study the effect in more detail, and we describe in this paper the results of our analysis and the possible explanations.

In Sect. 2 we discuss the evidence of discrepancies in $< V_{abs} - V_{emi} >$ found in the past and in other surveys, and in Sect. 3 we present the discrepancy detected in the ESP data. In Sect. 4 we describe the tests we have performed on the ESP data, exploring instrumental and other effects which could in principle affect our results; in Sect. 5 we analyse in detail the biases on velocity measurements due to the choice of the template spectra; in Sect. 6 we discuss if such a discrepancy can be partly due to a real, physical effect; our conclusions are in Sect. 7.

2. Systematic differences between absorption and emission line redshifts in previous surveys

Systematic differences in redshift measurements have been detected and discussed in the past. For example, Roberts (1972) found a systematic difference between the HI and the optical redshifts of galaxies in the velocity range between 1200 and 2400 km/s, which he attributed to the blending of galaxian and sky Ca II H and K absorption lines. A small effect in the same range of velocities was also found by Sandage (1978), with $< V_{HI} - V_{emi} >= -33 \pm 22$ km/s and $< V_{HI} - V_{abs} >= -103 \pm 37$ km/s, i.e. a positive difference between absorption and emission velocities corresponding to about +70 km/s. Sandage applied then a zero-point correction of +30 km/s to the redshifts, for consistency with HI velocities, but Tonry & Davis (1979) found that the redshifts of the galaxies they had in common with Sandage were consistent with Sandage redshifts only if his correction was not applied.

These puzzling results were not isolated. Corwin & Emerson (1982) analysed the spectra of 71 galaxies, and for 24 galaxies with both absorption and emission velocities they found $< \Delta V >=< V_{abs} - V_{emi} >= +64 \pm 16$ km/s (hereafter ΔV will always indicate the difference $V_{abs} - V_{emi}$). Lewis (1983) found a zero-point error of about 30 km/s in the data of Shectman, Stefanik & Latham (1983), for which $< V_{abs} - V_{emi} >$ was systematically negative. Interestingly enough, when regarding the cases with the largest residuals, he found that the V_{HI} velocity was nearer to the V_{abs} and also that $< V_{abs} - V_{emi} >$ was systematically positive. He concluded that these cases "[...] are most probably explained as large gas outflows from the nucleus". Similarly, Mirabel & Sanders (1988) measured $< V_{HI} - V_{opt} >\sim 87$ km/s, where V_{opt} refers to emission line velocities, for a sample of ultra-luminous dusty IRAS galaxies; they concluded that "The discrepancy could be due to optical line-emitting gas moving radially, probably outward, in the central regions of luminous infrared galaxies. If such outwardly moving emitting-line gas is mixed with dust, the attenuation of emission from the far side leads to an observed optical redshift below systemic." Similar results have been found for the [OIII] $\lambda5007$ line in the Narrow Line Region of AGNs (see Wilson & Heckman 1985 and Sect. 4).

The above discussion shows that a) non-negligible systematic zero-point differences are a common problem in redshift surveys; b) sometimes, a systematic difference may be due to physical reasons, as in the case of ultraluminous infrared galaxies; c) with small number of galaxies, it is difficult to determine the amplitude and the reasons of the difference.

A better analysis of this problem can be done with larger samples. For the main surveys where both absorption and emission line redshifts are available, we show in Table 1 the acronym of the survey (column 1), the number N_g of galaxies in the sample (column 2), the limiting apparent magnitude (column 3) and the mean $< V_{abs} - V_{emi} >$ with its error (column 4). At relatively bright magnitudes ($b_J \leq 17$), we have 3 main redshift surveys where both V_{abs} and V_{emi} are available for more than 100 galaxies: the Anglo-Australian Redshift Survey (AARS; Peterson et al. 1986), the South African Astronomical Observatory Redshift Survey (SAAO; Menzies et al. 1989), and the Stromlo-APM Redshift Survey (Loveday et al. 1996). As apparent from Table 1, the first two surveys do not show any systematic difference between V_{abs} and V_{emi}. Loveday et al. (1996) find $< \Delta V >\sim -19$ km/s for the Stromlo-APM redshift survey, and conclude that this value "is negligible compared with the rms difference of 124 km/s". Indeed in the literature the average value of ΔV is often compared only with the rms of the ΔV distribution. However, as Loveday et al. (1996) have 825 galaxies with reliable absorption and emission velocities, this implies a standard error on the mean of about 4 km/s, i.e. the value of -19 km/s formally differs from zero at more than 4σ level. Such a systematic effect is obviously negligible, but in other cases it is not, and it is important to keep distinct the rms of the ΔV distribution from the standard error of the mean.

There is indeed another source of redshifts, which gives a somewhat different result: it is the redshift catalogue for a magnitude limited sample ($b_J \leq 16.5$) obtained with the FLAIR multi-object spectrograph (Parker & Watson 1990). For a sam-

Table 1. Mean $\Delta V = < V_{abs} - V_{emi} >$ for various recent redshift surveys

Survey	N$_g$	b_J	$< V_{abs} - V_{emi} >$ (km/s)
SAAO	142	~ 15	-7 ± 7
AARS	165	~ 17	-2 ±4
STROMLO-APM	825	17.15	-19 ± 4
ESP	742	19.4	+94 ± 6
BES	97	21.5	+129 ± 10

ple of 80 galaxies, the measures of redshift made on the red part of the spectrum give $< \Delta V >= +52$ km/s, with rms 21 km/s: this means that the discrepancy is significant. Among various tests, Parker & Watson show that velocity measures of the night sky emission lines are systematically shifted of about -15 km/s. On the other hand, absorption velocities are measured by cross-correlating with only one template and, as they notice, an error of ~ 50 km/s on the published velocity of the template could explain the difference. For these reasons, it is not possible to prove the existence of a real discrepancy in the FLAIR data.

The situation is different when looking at results obtained at fainter magnitudes. For the Durham/Anglo-Australian Telescope faint galaxy redshift survey (Broadhurst et al. 1988, hereafter BES), with an apparent magnitude limit $b_J \leq 21.5$, 97 galaxies have both absorption and emission velocity. While Broadhurst et al. do not discuss the problem, from their published velocities and their quoted redshift precision of ~ 100 km/s, we find a systematic difference $< V_{abs} - V_{emi} >\sim +129 \pm 10$ km/s.

3. $< V_{abs} - V_{emi} >$ discrepancy in the ESP

While the results of most previous surveys are based on a relatively small number of galaxies, we have a catalog of 742 galaxies for which both emission and absorption line velocities ([OII]λ3727, H_β, [OIII]λ4959 & λ5007) have been measured. This data set is a subsample of the recently completed ESO Slice Project (for more details see Vettolani et al. 1997, 1998), a statistically complete redshift survey of 3342 galaxies to a depth of $b_J = 19.4$, selected from the Edinburg/Durham Southern Galaxy Catalogue (Heydon-Dumbleton et al. 1988, 1989; Collins et al. 1989). Observations were carried out at the 3.6m ESO telescope at La Silla, with the multi-fiber spectrographs OPTOPUS (Lund & Surdej 1986) and MEFOS (Felenbok et al. 1997). Exposure times were fixed, with 2 half an hour exposures for each field. The spectral coverage of the survey ranges from 3730 Å to 6050 Å, sampled at $\simeq 4.5$ Å/pixel (corresponding to ~ 270 km/s at 5000 Å). Redshifts were determined using the *IRAF*[1] external package *rvsao*, developed at the Smithsonian Astronomical Observatory. The absorption line redshifts were measured with the task *xcsao*, based on a cross-correlation technique, comparing the observed galaxy spectra with 8 stellar template spectra, observed by us with the same instrumental set up, and selecting the velocity given by the template with the smallest error, while the emission lines were directly measured with the task *emsao*. The median internal velocity error for our data is ~ 60 km/s. The appropriate heliocentric correction was applied to all velocities.

In the cross-correlation technique, the quality of a spectrum can be judged by its R parameter, defined as:

$$R = \frac{h}{\sqrt{2}\sigma_a} \tag{1}$$

where h is the height of the true cross-correlation peak and $\sqrt{2}\sigma_a$ is the height of an average, noise peak. The mean error on the measured shift of the spectrum, binned on a logarithmic scale, is $\propto (1+R)^{-1}$; therefore a larger value of R generally corresponds to a lower error (see Tonry & Davis 1979 for a detailed discussion).

The task *emsao* finds emission lines, determines the peak wavelength of each identified line through gaussian fitting and computes its redshift. If more than one emission line redshifts are measured, *emsao* combines them into a single radial velocity. In our process of data reduction, each galaxy spectrum was carefully checked by eye, in order to avoid spurious identifications.

We carefully examined the galaxies with the largest $< V_{abs} - V_{emi} >$ in the ESP survey before building the final catalogue. Apart from a few cases where the difference was obviously spurious, due to an error in writing one velocity, or in the identification of an emission line, most of the remaining large ΔV were confirmed, and in these cases a genuine physical explanation is probably required (see Sect. 4).

We find for 742 galaxies $< \Delta V >= 93.7 \pm 6.1$ km/s, with a standard deviation $\sigma = 166$ km/s, while the corresponding weighted estimates are $< \Delta V >= 90.8 \pm 5.0$ km/s and $\sigma = 138.5$ km/s, with no statistically significant skewness. We point out that that the formal error values of the IRAF tasks *xcsao* (for absorption line velocities) and *emsao* (for emission line velocities) were multiplied respectively by the factors 1.53 and 2.10, in order to obtain estimates of the true errors (these corrections are based on the analysis of galaxies observed more than once, see Vettolani et al. 1998). In this paper the weighted estimates and the associated errors are always computed applying these correction factors.

The observed width of the ΔV distribution results in principle from the convolution of the intrinsic width of the distribution (σ_{int}) with the measurement error distribution. Applying a maximum likelihood technique (see Maccacaro et al. 1988), which takes into account the error associated with each measurement, we find $\sigma_{int} \sim 40$ km/s, with a three sigma allowed range from 0 to 68 km/s. Therefore, the effect responsible for the positive $< V_{abs} - V_{emi} >$ cannot have a very large intrinsic dispersion.

As shown in Table 1, in the ESP and BES surveys the absorption line velocities are systematically higher than emission line velocities, in contrast to the shallower surveys, where no discrepancy is detected. In Fig. 1 we show the velocity histograms for the ESP and the BES, where the ΔV asymmetry with respect to 0 (dashed line) is clear (notice that the adopted

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[1] *IRAF* is distributed by the National Optical Astronomy Observatories, which is operated by AURA Inc. for the NSF.

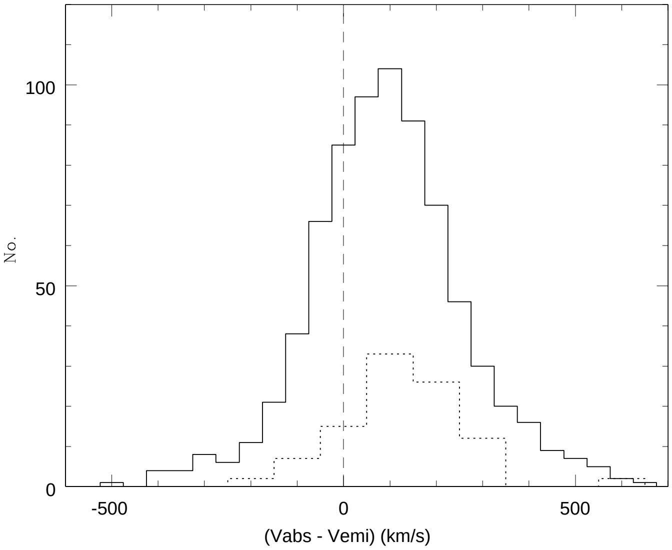

Fig. 1. Histogram of the velocity difference $\Delta V = V_{abs} - V_{emi}$; solid line: ESP; dotted line: BES.

bin for the BES is twice as large as for the ESP data, since the number of objects in the BES survey is smaller).

In order to investigate the possible systematic effects which could give rise to the observed $< V_{abs} - V_{emi} >$ in the ESP, we have carried out a large number of tests on our data. Concerning the quality of the spectra, it is remarkable that the velocity shift is confirmed -and even larger- for redshifts which have a high R parameter, rising from 90.3 ± 5.1 km/s for $R \geq 2$ (694 galaxies), to 108.5 ± 9.5 km/s for $R \geq 7$ (100 galaxies). Restricting the sample to the 54 galaxies showing at least 4 emission lines and with $R \geq 3$ gives $< V_{abs} - V_{emi} >= +90.1 \pm 15.1$ km/s.

In Table 2 we show in column 1 the limits defining the subsample (respectively minimum and maximum apparent magnitude, absolute magnitude, and redshift), in column 2 the number of galaxies N_g, in column 3 the weighted average $< \Delta V >$ with its error, and in column 4 the rms. From Table 2 it appears that the amplitude of the effect is smaller at brighter apparent magnitudes ($b_J \leq 18$), at lower redshifts ($z \leq 0.08$), and at fainter absolute magnitudes ($M \geq -19$). The uncertainties are quite large, and it is not possible to establish a significant trend, but the data suggest an increase of the effect with distance and absolute magnitude.

Table 2. Velocity differences as a function of apparent magnitude, redshift, and absolute magnitude for the ESP survey (weighted estimates).

m	N$_g$	ΔV	rms
$15 \leq m < 18$	142	71.6 ± 9.6	115.2
$18 \leq m < 19$	350	98.0 ± 7.3	132.8
$19 \leq m \leq 19.4$	249	99.1 ± 9.7	166.2
z	N$_g$	ΔV	rms
$0.00 \leq z \leq 0.08$	178	72.1 ± 9.1	107.2
$0.08 \leq z \leq 0.12$	239	99.7 ± 8.6	133.5
$0.12 \leq z \leq 0.16$	154	100.7 ± 11.7	154.3
$0.16 \leq z \leq 0.24$	158	100.2 ± 12.4	176.5
M	N$_g$	ΔV	rms
$-18 \leq M \leq -16$	67	84.9 ± 16.4	110.8
$-19 \leq M \leq -18$	164	81.6 ± 10.3	121.4
$-20 \leq M \leq -19$	278	93.4 ± 8.1	146.1
$-21 \leq M \leq -20$	216	99.1 ± 9.5	149.1

As the effect is significant in all magnitude and redshift bins, we can exclude that it is due to the blending with some specific sky lines.

4. Possible instrumental errors

4.1. Velocities zero-point

In the cross-correlation method, the most important point of concern is of course the zero-point of the templates. Therefore we measured the velocities of three SAO radial velocity standard stars; averaging the values obtained from our 8 ESP templates, we find that the velocity estimates of the 3 stars agree with the literature values within a few kilometres per second. Moreover, a comparison with 7 galaxies for which HI velocities are available shows that the mean zero-point of the 8 stellar templates is lower than the mean HI velocities by -17 ± 10 km/s. In Table 3 we give the velocity difference $V_{ESP} - V_{HI}$, where V_{ESP} is the velocity obtained from the cross-correlation and V_{HI} is the literature velocity, for each template.

Table 3 shows that our 8 templates give consistent results. The template which seems to give the largest underestimate of the velocity (relatively to the HI velocities), is no.7

The 9 galaxies with measured velocity we have in common with the Stromlo-APM redshift survey (Loveday et al. 1996) give a mean difference $V_{ESP} - V_{APM} = -7.9$ km/s. This means that we expect a negligible zero-point error, with possibly a small *underestimate* of the true absorption velocity: if we should apply such a correction, the systematic difference between V_{abs} and V_{emi} we find would be even larger.

4.2. Wavelength calibration

After excluding a zero-point error, the next candidate for an explanation is a calibration problem. For example, we can suppose that in our wavelength calibration there is a systematic error between the blue and the red parts of the spectrum, and that the velocity discrepancy is due to the underestimate of the [OII]λ3727 line redshift.

Table 4 shows how the error weighted estimate of $< \Delta V >$ depends on the emission lines detected in the spectrum (see also Fig. 2); we have listed all the possible cases except when only one of the two [OIII] lines is present.

From Table 4 we see that all emission lines give positive $< V_{abs} - V_{emi} >$, and that the values are all consistent, except for the H_β and the [OII]λ3727 + [OIII]λ4959 & λ5007 lines, which give respectively the smallest and the largest velocity difference.

The most important implications of Table 4 are that a) the effect does not depend only on [OII], thus excluding a mismatch

Table 3. V_{ESP} - V_{HI} obtained with our 8 templates on 7 galaxies with HI redshifts.

Gal. no.	1	2	3	4	5	6	7	<V> (km/s)
ESP template 1	21	-9	7	0	39	-29	-52	-3 ± 11
ESP template 2	57	-37	40	1	-4	-29	-46	-3 ± 15
ESP template 3	6	-33	-2	-20	3	-31	-55	-20 ± 8
ESP template 4	14	-23	-8	-20	26	-24	-51	-12 ± 10
ESP template 5	21	2	-1	-19	32	-37	-67	-10 ± 13
ESP template 6	38	-48	24	-17	-16	-35	-52	-15 ± 13
ESP template 7	15	-50	-27	-60	-19	-34	-62	-34 ± 10
ESP template 8	18	-17	1	-21	5	-36	-60	-17 ± 10

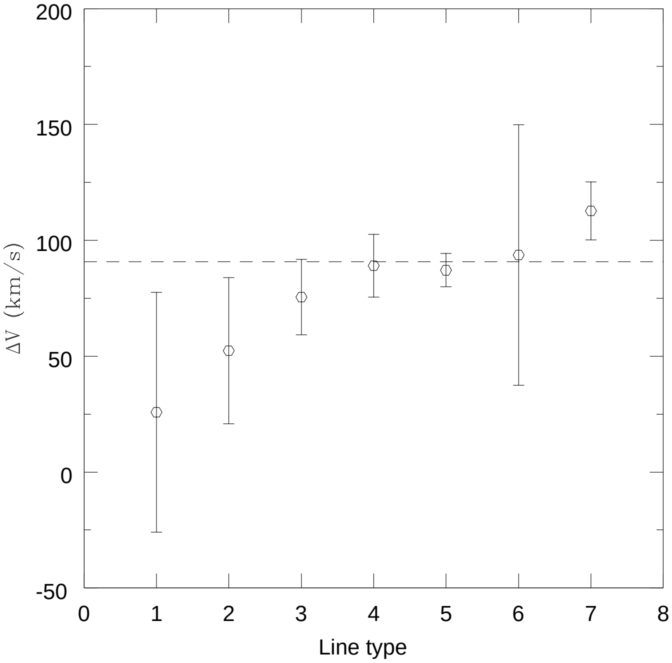

Fig. 2. $< V_{abs} - V_{emi} >$ (with 1σ errors) as a function of the lines present in the spectrum; 1 = H_β, 2 = H_β + [OIII]a & b, 3 = H_β + [OII], 4 = H_β + [OII] + [OIII]a&b, 5 = [OII], 6 = [OIII]a&b, 7 = [OII] + [OIII]a & b. The dashed line shows the average value found for the whole sample.

Table 4. Error weighted $< V_{abs} - V_{emi} >$ as a function of the emission lines detected in the spectrum

Lines	N$_g$	ΔV	error
H_β	8	26	52
H_β + [OIII]a & b	22	52	32
H_β + [OII]	68	76	16
H_β + [OII] + [OIII]a&b	88	89	14
[OII]	430	87	7
[OIII]a&b	7	94	56
[OII] + [OIII]a&b	64	113	13
All	742	91	5

due to the particular shape of the line (as [OII] is in fact a doublet which is not resolved in our spectra); b) we have a very good calibration both in the blue and in the red part of the spectrum.

For the 8 galaxies where only the H_β emission line has been detected, the mean emission velocity is formally consistent with the absorption velocity, but is also consistent with the total sample average at the 2σ level. We stress that the H_β emission line shape is not easy to fit. We point out also that the absorption H_β rest wavelength usually assumed for galaxies (and for example used in $IRAF$) is at 4863.9 Å i.e., shifted by 2.6 Å with respect to the laboratory wavelength. This value was first given by Sandage (1975; the Sandage values are also reported by Loveday et al. 1996) and implicitly attributed to the blending with other lines at low resolution. We do not know of more recent tests about this shift, which should depend on the instrumentation and the galaxy type. It is worth noticing that, in order to find the "effective" wavelengths of blended lines in galaxies, Sandage explicitely assumed that the emission lines indicate the true velocity of the system; any systematic velocity of the emission lines relative to the galaxy velocity would be reflected in the values of the absorption wavelengths.

With the absorption H_β line at a slightly larger wavelength than the emission H_β, the velocity of the latter might be underestimated, which would justify the small difference with the other emission lines. On the other hand, supposing that in our case the effective rest wavelength of the H_β absorption line is smaller than the value given by Sandage (1975), -i.e. nearer to the laboratory wavelength- then assuming the Sandage value we would underestimate the absorption H_β line redshift and, consequently, the amplitude of ΔV.

Table 4 tells us that if such effects are present in our sample, they are not large.

4.3. Other possible errors

We have taken into account many other possibilities.

It is well known that the [OII]$\lambda3727$ line is in fact a doublet, unresolved at our resolution. We have checked that this cannot significantly affect our fit and, as we have shown, the discrepancy is present also with the other emission lines.

Before cross-correlating a spectrum, the emission lines of the galaxy, if present, were removed. Within *xcsao* it is also possible to perform this task automatically, but we decided to remove emission lines manually, after a comparison of the results obtained with the two methods (varying also the parameters in the automatic procedure), as we found that the typical

Table 5. Average cross-correlation velocity differences ΔV_{cc} measured in a subsample of ESP galaxies with our 8 templates. The velocity obtained with the ESP template no.1, V_1, is conventionally taken as a reference.

ESP Field	$< V_1 - V_2 >$	$< V_1 - V_3 >$	$< V_1 - V_4 >$	$< V_1 - V_5 >$	$< V_1 - V_6 >$	$< V_1 - V_7 >$	$< V_1 - V_8 >$
Field 104							
N_g	24	30	29	28	27	29	28
ΔV_{cc}	11.6	-17.9	-52.6	9.3	15.4	-45.8	8.4
Field 106							
N_g	9	16	19	16	13	17	18
ΔV_{cc}	41.2	-7.6	-55.6	-19.2	64.5	-33.7	4.8
Field 107							
N_g	22	29	29	28	24	30	30
ΔV_{cc}	38.9	1.4	-29.2	15.3	42.7	-15.2	20.2
Field 108							
N_g	22	28	29	30	22	29	29
ΔV_{cc}	8.6	-15.0	-38.8	13.0	12.7	-20.9	8.4
Field 109							
N_g	12	22	22	19	14	22	22
ΔV_{cc}	37.4	-0.7	-32.1	29.9	56.5	-14.8	13.9
Field 121							
N_g	20	31	31	31	22	31	32
ΔV_{cc}	-8.5	-8.1	-35.7	10.4	12.9	-13.4	4.4
Field 145							
N_g	12	16	16	16	14	15	16
ΔV_{cc}	49.4	-8.3	-57.6	5.7	51.2	-35.2	-2.2
Field 164							
N_g	20	23	23	23	22	23	22
ΔV_{cc}	14.9	5.7	-37.4	-9.5	34.4	-7.9	17.4
Total N_g	141	195	198	191	158	196	197
$< \Delta V_{cc} >$	20 ± 7	-7 ± 3	-41 ± 4	8 ± 5	32 ± 7	-23 ± 5	10 ± 3

difference in the velocity is ~ 20 km/s, with no evidence of a systematic overestimate with our method.

In the cross-correlation method the continuum is fitted and subtracted from the spectrum. Therefore we have changed the fitting functions and orders, without any significant variation in the results. These tests cannot exclude a systematic difference due to the way *xcsao* normalizes the continuum; but the fact that the effect is present at very different redshifts suggests that this is not the case.

The fact that the velocity difference is significant in all magnitude and redshift bins (see Table 2) excludes also that it may be due to the blending with some sky lines (as in the case of the Roberts effect).

Before concluding that the velocity discrepancy between absorption and emission lines is real, we have still to focus on an important aspect of the cross-correlation technique. Such technique relies on information external to the data: the template spectra. In the cross-correlation method we assume that the best redshift measurement is given by the best-fitting template. In the next section we will carefully check the validity of this assumption.

5. Dependence of the redshift measurements on the template spectra

In addition to the ESP, another recent redshift survey presents a systematic discrepancy between absorption and emission line redshifts: it is the Las Campanas Redshift Survey (LCRS; Shectman et al. 1996). When discussing the data reduction for the LCRS, Shectman et al. (1996) note that a systematic bias "creeps into cross-correlation velocities for the emission line galaxies". They ascribe this bias to systematic differences in the absorption-line spectra of standard templates (which are usually late-type stars) and emission line galaxies, in particular to a blend between the $H_\epsilon \lambda 3970$ and Ca II H lines. This blending was already tabulated in the classical work by Humason, Mayall & Sandage (1956), and described by Sandage (1978). Humason et al. (1956) list 3 possible effective wavelengths for the blend between H_ϵ and the Ca II H line, depending on their relative intensities: 3968.54Å, 3969.01Å and 3969.23Å, with the Ca II H rest wavelength line at 3968.38Å. Sandage (1978) discusses the dependence of the blending on the galaxy type, concluding that it can be of the order of ~ 100 km/s.

Indeed using a template with strong Balmer lines, Shectman et al. (1996) reduce the systematic effect to about 15 km/s.

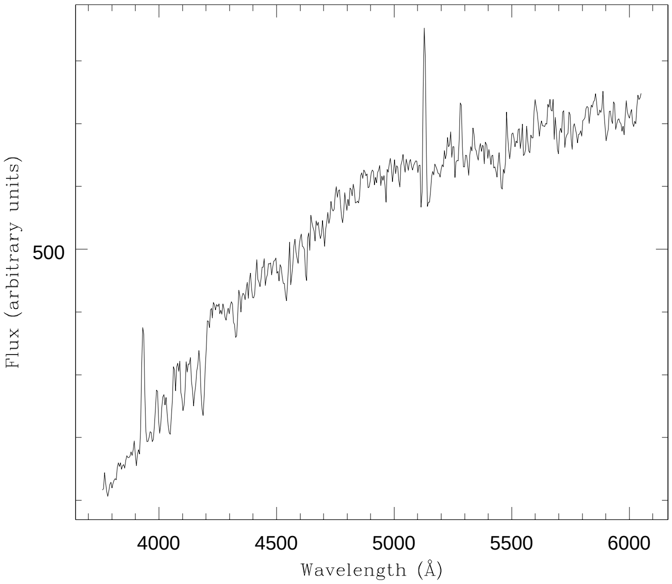

Fig. 3. Spectrum of a galaxy with $V_{abs} - V_{emi} \sim 30$ km/s.

Therefore they use this template for galaxies with emission lines and two standard templates for all the other galaxies. However, we think one should be careful in taking this possibility as a definitive explanation, only on the basis of the *a posteriori* agreement between V_{abs} and V_{emi}. It would be surprising that the results of the cross-correlation should depend so critically on one line (even if the H line is surely important), and other lines should conspire to give this difference (as suggested by Shectman et al. 1996).

We performed some tests cross-correlating the 3 LCRS templates (kindly provided by H.Lin) together with our 8 star templates to our spectra. We confirm that the LCRS template with strong Balmer lines gives systematically lower velocities than the other ones. However, the templates which give the best-fit to galaxy spectra are systematically the standard ones, while the template with strong Balmer lines usually gives a lower R, even in cases where there are strong emission lines. Moreover, such template should give lower absorption redshifts only for galaxies with a significant discrepancy between V_{abs} and V_{emi}, while it gives lower redshifts also for other galaxies. For example, in the case of the spectrum shown in Fig. 3, the standard Shectman templates perform better, and are consistent with our 8 templates, while the non-standard Shectman template performs more poorly, and gives a velocity about 100 km/s lower: but in this spectrum, the emission line velocity is consistent with the absorption one (only 30 km/s lower), so applying the special template to this emission line spectrum would in fact underestimate the redshift! This illustrates the main risk of using a different template for emission line galaxies: it may solve the $< V_{abs} - V_{emi} >$ problem in a statistical sense, but it might not work with the individual galaxies.

However, this does not exclude the possibility that a systematic effect can be introduced by the choice of a template. In order to clarify the issue, we have compared the velocities given by *all* our 8 templates for each galaxy in a subset of 8 ESP fields. The results are shown in Table 5, where we report in the first column the ESP field number, and in columns from 2 to 7 the mean difference $< V_1 - V_J >$, $J = 2, 8$, between the velocities measured with the ESP template no.1 (arbitrarily chosen as a reference) and with each one of the other 7 ESP templates.

Table 5 shows in a clear way that systematic differences do exist: for example, templates no.4 and no.7 give on the mean larger velocities. The systematic effect between template no.4, which gives the largest velocity, and template no.6, which gives the lowest velocity, is of about 70 km/s. Notice that this *cannot be due* to a zero-point error. This becomes very clear when comparing Table 5 with Table 3, which shows the zero-point shifts of the ESP templates as estimated from a comparison with the HI velocities of 7 galaxies. From Table 3 we see that the ESP template no.7 gives the lowest estimate of the HI velocities, and we would expect $< V_1 - V_7 > \sim +30 \pm 15$ km/s instead of $< V_1 - V_7 > \sim -23 \pm 5$ km/s; for template number 4, from our comparison with HI velocities we would have expected $< V_1 - V_4 > \sim +9 \pm 15$ km/s, instead of $< V_1 - V_4 > \sim -41 \pm 4$ km/s!

We conclude that different templates give systematically different velocities, probably because each template fits in a different way the observed galaxy spectra. In the light of our results, the velocity difference between the 3 templates by Shechtman et al. (1996) appears to be a particular case.

Can the results shown in Table 5 explain our $< \Delta V >$ problem? This would be the case if the templates no.4 and no.7 gave a systematically smaller error (as in the ESP we have attributed to each galaxy the velocity of the best-fitting template). We have indeed found that these two templates were used for 47% of the galaxies in the subset of fields shown in Table 5. However, replacing velocities obtained with the two templates giving systematically larger velocities, with the best one obtained by any one of the other templates, the resulting $< V_{abs} - V_{emi} >$ is $\sim +65$ km/s. The discrepancy is reduced, but still present; and should we after all rely on templates which perform worse but which give a “better” result?

That things are not so simple is shown by another example. We have chosen a spectrum with high signal-to-noise ratio (Fig. 4), showing a difference $V_{abs} - V_{emi}$ of ~ 200 km/s, and we have looked at the values given by our templates and by the Shectman templates (Table 6). It is clear that the template with strong Balmer lines (LCRS A template) gives a lower value, but not sufficient to explain the difference; moreover, it performs very poorly. On the other hand, when we fit the main absorption or emission lines with a gaussian, we find the values shown in Table 7. In this case the cross-correlation has apparently overestimated the redshift by ~ 100 km/s relatively to the gaussian fitting measure. It can be noticed that neither template no.4 nor template no.7 are among the 3 best-fitting templates, and template no.6 gives a relatively high velocity. We still find a positive $\Delta V \sim 100$ km/s; however, if we could generalize this result, by concluding that the cross-correlation overestimates the redshift by 100 km/s, the velocity bias would obviously vanish. The problem is that for spectra with a lower S/N ratio the direct

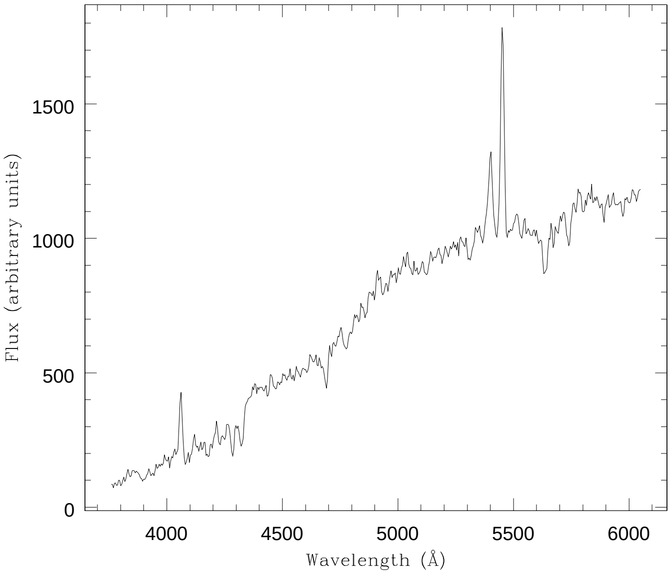

Fig. 4. Spectrum of a galaxy with $V_{abs} - V_{emi} \sim 200$ km/s.

Table 6. Results of the cross-correlation for the spectrum of Fig. 4.

Template	Velocity	Error	R
ESP template 2	26822	32	11.8
ESP template 8	26858	33	11.7
ESP template 6	26850	35	11.1
LCRS std templ.	26831	35	10.5
ESP template 1	26838	37	10.0
ESP template 4	26837	44	8.9
ESP template 7	26831	45	8.6
ESP template 3	26793	39	8.2
LCRS A template	26798	78	4.1
ESP template 5	20141	83	2.0

Table 7. Results from gaussian fitting of the absorption and emission lines in the spectrum of Fig. 4.

Line	λ	Velocity
Ca II K	4284.8	26758
Ca II H	4323.15	26791
G	4688.31	26739
Mgb	5636.76	26728
FeCa	5738.75	26729
[OII]	4059.6	26727
[OIII]4959	5399.73	26650
[OIII]5007	5452.55	26688

measure of absorption lines is much more uncertain, and when the velocity difference between absorption and emission lines is around 100 km/s the Gaussian fitting of a few lines is not sufficiently accurate.

We tried to avoid this problem by selecting a subset of 16 spectra with a large R parameter, most of them with 4 emission lines, and with a positive ΔV: this subset has an average $\Delta V = 124$ km/s. We have shifted these spectra to the rest wavelength expected from their measured *absorption line* velocity, as given by *xcsao*; then we have added these spectra, to build a composite spectrum with higher S/N ratio. We show this spectrum in Fig. 5. Before addition, the individual spectra were resampled to 2048 pixels. We have measured the wavelengths of the main lines through a gaussian fit. We find that the emission lines are systematically blueshifted: the [OII]3727 by -80 km/s, the H_β by -99 km/s, and the 2 [OIII] lines respectively by ~ -147 km/s and -148 km/s. The [OIII] lines show also an asymmetric "bump" in their blue tail.

On the other hand, the wavelength of the Ca II H line is at 3968.5 Å, corresponding to zero km/s. However, all the other absorption lines are also blueshifted. For example, the Ca II K line has a shift corresponding to -96 km/s. The H_δ line gives -73 km/s, the G-band -70 km/s, the FeCa -39 km/s. The absorption H_β and Mgb lines are also present, but they are quite asymmetric, so that a gaussian fit cannot be a reliable measure.

Computing the average velocity of the selected lines with their errors, we find $< V_{abs} >= -56 \pm 17$ km/s including the Ca II H line, or $< V_{abs} >= -70 \pm 12$ km/s excluding it, and $< V_{emi} >= -119 \pm 17$ km/s.

Before drawing strong conclusions, we should emphasize that the Gaussian fit is not very accurate, as it depends on the estimate by eye of the continuum; moreover, the spectra have been chosen for their strong absorption lines, which implies that they are not among those spectra with the strongest emission lines, and might not be representative of the total sample; finally, the effect will be somewhat diluted as each galaxy has a different ΔV.

We have also applied the cross-correlation method to the composite spectrum. The formally lowest errors are obtained with the standard Shectman template, giving $V = -20$ km/s ($R = 10.6$), and our template no.8, giving $V = 14$ km/s ($R = 9.0$). The LCRS A template, with strong Balmer lines, performs poorly ($R = 6.56$) but gives $V = -72$ km/s, a measure in good agreement with the estimate derived from the gaussian fit of the lines.

With all the uncertainties we have mentioned, it seems that the cross-correlation overestimates the redshift, apparently giving a large weight to the CaII H line near the 4000Å break, thus confirming, at least in part, the suggestion by Shectman et al. (1996). It appears that in our case the effective rest wavelength should be fixed to about 3869.5 Å (comparable to the third wavelength value for this line listed by Humason et al. 1956), instead of the usual 3968.5 Å.

We cannot conclude, however, that this effect can completely explain the discrepancy with the emission line redshift. Notice in fact that in the average spectrum the two [OIII] emission lines are still discrepant by about 70 km/s relatively to the average of the absorption line velocities (excluding the Ca II H line).

Moreover, as the above examples have shown, for a given galaxy we have no way to decide *a priori* which is the template giving the best estimate, if we leave the best-fit criterium. For the above reasons, we decided to measure the redshifts of all

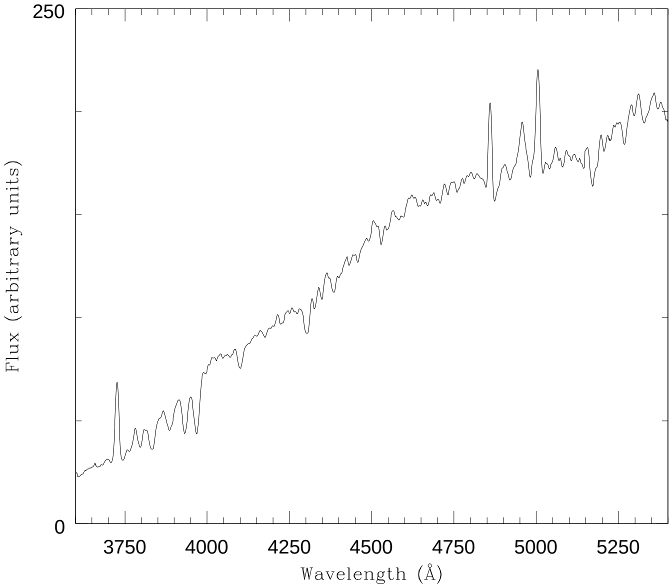

Fig. 5. Coadded spectra of 16 galaxies, after having been shifted to rest wavelengths according to their measured *absorption line* velocity.

spectra in the ESP with the technique of the best-fitting template, without forcing a given template to fit a given class of galaxies.

On the other hand, the choice of the template which gives velocities in agreement with emission line velocity means we assume that the system velocity is given -on the average- by the emission line velocity. In the absence of a definitive understanding of the bias, we think it is important to check that emission lines are on the average at rest, and that they cannot have at least partially, a physical origin. We will briefly consider this possibility in the next section.

6. Could it be a real effect?

A relative shift of absorption and emission lines can be a consequence of significant infall or outflow of gas in a galaxy. Cowie et al. (1995) in fact find evidence of infall of gas from their observations of distant galaxies. Assuming that at least part of the velocity shift detected in the ESP is real, we have to find a relatively common process internal to galaxies which can give rise to “peculiar motions”, with outflow of the line emitting gas of ~ 100 km/s.

As briefly mentioned in the introduction, a similar effect exists for the Narrow-Line Region of AGNs, consisting in a systematic blueshift of the [OIII]5007 line velocity relatively to the HI or absorption line velocity, and amounting to about 50-100 km/s (Wilson & Heckman 1985), with the difference ranging between -250 and 250 km/s. It can be due to the asymmetry of the line, generated by an outflow component on the near side of the AGN (see Peterson 1997).

It is known that emission lines from normal galaxies tend to trace the young stars formed in HII regions located on the spiral arms of late-type galaxies, while the absorption lines dominate the stellar light from the inner bulge component of galaxies (Vogel et al. 1988; see also Knapen et al. 1992). However, there is no evidence that the velocity bias we see is connected to the rotation of galaxies as there is no clear correlation between $V_{abs} - V_{emi}$ and galaxy inclination, as we could determine from the axial ratios.

While individual HII regions usually have thermal expansion velocities of $10 - 20$ km/s, which is insufficient to account for the result, there is growing evidence of substantial amounts of diffuse ionized gas at $T \sim 10^6$ K, shock heated by either supernovae or stellar winds, in some galaxies; this gas can have expansion velocities ≥ 100 km/s after 10^5 yrs (Spitzer 1990). Such gas has been conjectured to contribute as much as 50% of the line emission in some star-forming galaxies and can propagate to scale-heights ($\simeq 5$ kpc) above the galaxy disk forming “galactic fountains” of gas. As already noted, velocity shifts of 100 km/s between optical emission line galaxies and 21cm observations of the neutral gas component have been found in ultra-luminous dusty IRAS galaxies (Mirabel & Sanders 1988). In these systems the effect is explained in terms of line-emitting gas moving radially outward in the central regions of such galaxies. The presence of large quantities of dust, mixed with the gas, provides the necessary attenuation of the emission from the far side of the galaxy.

In the ESP survey we can only identify a handful of Seyferts and since the survey is a complete optically selected sample, the velocity bias should be a more common feature of the overall galaxy population than was previously thought and not simply confined to extragalactic objects with exotic properties.

This could be related to a steady increase in the amount of turbulent gas within galaxies with look-back time. Radial motions of gas could have a significant role to play in galaxy evolution and may well provide a new probe of the early history of galaxies. On the other hand, at a fainter limiting apparent magnitude the fraction of intrinsically faint galaxies can increase due to evolution, and one could alternatively imagine that a population of dwarf, star-forming galaxies is responsible for the effect.

The fact that the $< V_{abs} - V_{emi} >$ may be larger at brighter absolute magnitudes and higher redshifts (see Table 2 for the ESP and Table 1 for a comparison with other surveys) might be more consistent with an evolution with redshift.

7. Conclusions

We have discussed in detail the errors associated to redshift determinations in the ESO Slice Project (Vettolani et al. 1997). We have found a systematic difference between absorption and emission line velocities of $\sim +100$ km/s and we have shown that the same effect is present in the Durham/Anglo-Australian Telescope faint galaxy redshift survey (Broadhurst et al.1988). In the case of the ESP, we have excluded problems of zero-point error or calibration. Such a discrepancy has not been detected in large shallower surveys.

Shectman et al. (1996) briefly discuss a similar effect for the Las Campanas Redshift Survey, which they have corrected by using a different template for emission line galaxies.

We have generalized the suggestion by Shectman et al. (1996), who identify as the main cause of the discrepancy the systematic difference between the absorption line spectra of the standard templates and the typical emission line galaxy, particularly the blend between the Ca II H and H_ϵ lines, an effect already discussed by Sandage (1978). We find in fact systematic effects even from template to template, apparently due to the way each template fits the galaxy spectra; this implies that the choice of the template significantly affects redshift measurements.

For the ESP data, we decided to use the best-fit template (i.e. the one giving the smallest error), as using a different template might introduce unknown biases in the redshift measurement.

In the lack of a definitive explanation, the common assumption that the true galaxy redshift is given - on average - by the emission lines, is plausible, but not proven. It should be verified that the bias cannot be due, at least partially, to emission lines, and that the sample is not biased, for some reason, towards galaxies with outflows. One can for example speculate that other factors may contribute to the effect, such as sampling of different parts of the galaxies, the different mix of morphological types, and evolution with look-back time. A collection of high resolution data of a sample of galaxies and of different templates will be necessary to give a definitive solution.

We feel it is important to stress the existence of such an “anomaly”: in view of future, large surveys, the templates used should be carefully checked and made publicly available[2], as already done by the LCRS group, to discover and quantify any systematic difference. Even if the amplitude of the effect is not large, it is quantitatively more important that typical zero-point shifts, and it is significant enough to affect for example measures of velocity dispersions and galaxy peculiar velocities, or the interpretation of results for very distant galaxies, as those which are reported by Cowie et al. (1995) and Steidel et al. (1997).

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[2] ESP templates are available at the following WWW address: http:/boas5.bo.astro.it/~cappi/esokp.html