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The cluster of galaxies Abell 151 *

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Abstract. We use a sample of 65 redshifts to study the kinematics and dynamics of the cluster Abell 151. Data on individual galaxies are presented, and the accuracy of the determined velocities are discussed as well as some properties of the cluster. The velocity data reveal a foreground group and a background population at the same redshifts as the closely projected cluster A 166.

Key words: redshifts of galaxies – clusters of galaxies – subclustering

1. Introduction

Redshift surveys in clusters of galaxies are needed to study their dynamical and evolutionary states, estimating parameters such as the mass, shape and distortion of the velocity field, presence of substructures or projected galaxies and groups, strength of dynamical friction and two-body processes and, in general, the present stage of their dynamical evolution. This information is useful not only to test scenarii of galaxy formation, but also of the formation and evolution of large structures. In clusters, the mean velocity is a key factor in deriving distances, permitting the study of matter distribution over very large scales. Within clusters the analysis of the velocity field can lead to an estimate of the virial mass, constraining models of the dark matter content. Galaxy velocity measurements provide information complementary to that obtained through X-ray observations of clusters. Both form basic pieces of information for the understanding of clusters. However, reliable parameters are derived from analysis of large samples of velocities. These are laborious to obtain, a task made more efficient by the wider use of multiobject spectroscopy. Here we examine for the first time the velocity and galaxy distribution in the cluster A 151.

A 151 is a richness 1 cluster of galaxies with $N_A = 72$ and a cDs RS-type (Struble & Rood 1987) for which 105 objects have been listed in Dressler's catalogue (1980). The cluster was not X-ray detected at an upper limit of 0.301710^{-3} in the *HEAO-A1* counts $cm^{-2}s^{-1}$ (Kowalski *et al.* 1984). Here we report 46 new redshifts to complement the existing velocity data. Section 2 presents the observations, data reduction techniques, and comparison with previous measurements. In Section 3, we discuss the structure of A 151 on the basis of the listed sample.

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*based on observations made at ESO, La Silla (Chile)

2. Observations and data reductions

The program of radial velocity measurements was carried out in December 1985 at the 3.60m telescope and in October 1990 at the 1.50m ESO telescope, both in La Silla (Chile). We used the multi-object spectrograph OPTOPUS at the 3.60m Cassegrain focus equipped with 35 separate optical fibers for collecting the light from galaxies spread over a field of 33 arcminutes diameter in the telescope focal plane (Cristiani *et al.* 1987). With the use of an F/1.9 dioptric spectrograph camera, each fiber output was projected onto an RCA CCD (512 × 320 pixel) detector with a fiber image size of 85 μm (2.8 pixels). The RCA chip was binned 2 × 1 to reduce noise, losing some spectral resolution in the process. A dispersion of 114 Å/mm was used, providing spectral coverage from 3800 to 5570 Å. Two fields were observed in the vicinity of the meridian plane in order to minimize refraction effects which can lead to small fibre/image offsets during the course of observations. A third field was lost due to cloudy conditions and forced large hour angle.

Observations with the 1.50m telescope were carried out in October 1990. We used the Boller and Chivens spectrograph at the Cassegrain focus, equipped with a 600 lines/mm grating blazed at 5000 Å and coupled to an RCA CCD (1024×640 pixels) detector with pixel size of 15 μm. A dispersion of 129 Å/mm was used, providing spectral coverage from 3750 to 5700 Å. The exposure times ranged between 30 and 60 min. according to the magnitude of the object. During the two runs, calibration exposures were made before and after each galaxy observation using an He-Ar source.

In the 1.50m run the stars HD196983 (K2III) and CPD-43^{o}2527 (K1III) (Maurice *et al.* 1984) were observed every night for the purpose of controlling the zero point in the velocity scale and for use as cross-correlation templates. Note that the use of a cold giant is a valuable criterion for a cross-correlation procedure since the profile of strong lines such as K, H, G, Hβ, or MgIb is not affected by gravity and/or metal abundance; it remains narrow, resulting from the Doppler core

Table 1. Heliocentric redshifts for galaxies in A 151.

GALAXY	NAME	R.A. (1950)	DEC. (1950)	TYPE	MAG.	HEL. VEL. $V \pm \Delta V$	N
51		01 04 30.6	-15 45 51	S0	15.0	11740 75	1
85		01 04 32.7	-15 33 55	S0/S	15.0	16079 35	a
88		01 04 35.3	-15 29 53	S0/a	16.0	16022 75	a
18		01 05 12.4	-16 14 11	S	15.0	15008 59	a
20	MCG-3-04-06	01 05 44.5	-16 09 01	S	16.0	12387 55	a
81		01 05 46.8	-15 36 33	E	16.0	15706 35	a
80		01 05 49.4	-15 37 17	S0/a	15.0	15925 38	a
35		01 05 59.4	-15 54 37	S0	16.0	29095 92	a
38		01 06 01.2	-15 50 32	S	15.0	13185 55	a
						13198 43	o
69		01 06 03.1	-15 39 48	E	15.0	16182 44	a
						16001 65	o
		01 06 03.4	-15 53 28			29518 73	o
68		01 06 04.7	-15 39 51	S	15.0	16522 53	a
		01 06 05.0	-15 51 44			28960 87	o
34		01 06 05.4	-15 53 14	S0	16.0	29893 97	o
24		01 06 12.0	-16 07 15	S0	15.0	12291 36	a
		01 06 13.3	-16 13 32	E		14050 120	1
33		01 06 13.5	-15 55 28	S	16.0	29939 94	o
67		01 06 13.6	-15 39 44	S0	16.0	15245 44	a
		01 06 15.2	-15 40 58		17.6	16177 80	2
66		01 06 15.5	-15 41 14	S0	15.0	17615 46	a
						17585 79	o
		01 06 16.1	-16 12 12	S0		15095 100	1
		01 06 17.2	-16 05 39			12528 78	o
57		01 06 17.5	-15 42 23	S0	16.0	15442 49	o
22	IC 78	01 06 19.5	-16 06 41	S	14.0	12054 55	a
						11952 98	o
56		01 06 19.5	-15 42 15	S	15.0	16850 46	a
						16901 43	o
		01 06 19.8	-15 39 26		17.4	31807 80	2
29		01 06 20.5	-15 57 38	S	15.0	16900 42	a
						16911 ?	o
65		01 06 20.6	-15 40 31	E	16.0	16657 60	a
63		01 06 21.3	-15 40 09	E	15.0	15919 75	o
64		01 06 21.3	-15 41 21	S0	16.0	16094 51	o
16	IC 79	01 06 21.5	-16 12 52	E	14.0	12644 38	a
62	MCG-3-04-08	01 06 22.2	-15 40 29	E	15.0	15432 37	a
						15447 63	o
		01 06 22.5	-16 05 25			12305 89	o
61	MCG-3-04-09	01 06 22.8	-15 40 20	D	14.0	16046 36	a
						15963 73	o
49		01 06 22.9	-15 46 26	S0	16.0	16264 63	o
		01 06 23.1	-15 39 27		17.3	16364 80	2
60	MCG-3-04-12	01 06 24.2	-15 41 14	S	14.0	16663 40	a
		01 06 25.3	-15 39 24		17.5	15700 80	2
48		01 06 25.6	-15 46 28	S0	16.0	14273 ?	o
78		01 06 27.1	-15 37 43	S0	16.0	14272 98	o
47		01 06 28.4	-15 48 22	S0/a	16.0	15230 63	a
5		01 06 28.7	-16 19 04	S0	15.0	11909 100	1
40		01 06 34.2	-15 49 28	E/S0	16.0	30769 ?	o
11		01 06 34.6	-16 16 31	S	16.0	16730 100	1
26		01 06 36.6	-16 03 14	S0	16.0	12301 96	o
10	IC 82	01 06 37.7	-16 16 00	S	14.0	16111 75	1
19		01 06 37.8	-16 07 39	S	16.0	11985 84	o

Table 1. (continued)

GALAXY	NAME	R.A. (1950)	DEC. (1950)	TYPE	MAG.	HEL. VEL. $V \pm \Delta V$	N
77		01 06 38.1	-15 38 10	E	16.0	29991 54	a
						30099 66	o
		01 06 38.1	-15 58 56			31186 95	o
76		01 06 38.5	-15 34 51	S0	15.0	16295 41	a
		01 06 41.5	-16 10 55	S0		11980 100	1
46		01 06 42.8	-15 45 44	S	15.0	15554 100	1
75	MCG-3-04-07	01 06 57.2	-15 37 41	E/S0	15.0	30364 41	a
						30353 67	o
		01 07 07.6	-15 49 50			15151 88	o
74		01 07 11.1	-15 37 47	S	15.0	15714 55	a
91		01 07 15.1	-15 24 35	S	15.0	6159 41	a
53		01 07 24.4	-15 45 05	S0	16.0	15469 60	a
44		01 07 37.6	-15 47 07	S	15.0	16530 55	1
43		01 07 37.8	-15 46 11	S	15.0	16425 100	1
52		01 07 39.4	-15 45 16	S0/S	15.0	16609 120	1
83		01 07 57.0	-15 31 19	Sa/0	15.0	17091 41	a
82		01 07 58.5	-15 31 44	E/S0	16.0	16266 40	a
42		01 08 13.1	-15 47 09	SB0	15.0	9947 60	1
41		01 09 16.3	-15 48 47	S+S	15.0	11865 100	1
41						16371 100	1

notes: a: 1m50 ESO telescope, **o**: 3m60 ESO telescope with OPTOPUS, **1**: Proust *et al.* (1988), **2**: Merrifield & Kent (1991)

with the stark-broadened wings (Praderie 1967); the two bright galaxies NGC439 and NGC441 with good measured radial velocities given by Lauberts & Valentijn (1989) were also observed in the same conditions, in order to use real galaxy templates in the cross- correlation procedure.

The data reduction of the OPTOPUS data was carried out using the IRAF package, while the 1.50m one was reduced by an IHAP image processing software. The radial velocities were derived from the cross-correlation procedure developed at Meudon in the EVE software. Wavelength calibration was performed using the He-Ar lamp reference. The lines are fitted with a third order polynomial; the average *rms* of the calibration is 0.25, and the resolution, as measured from the FWHM of a Gaussian fit to the He-Ar lines, is 5 Å.

The spectra were rebinned with a scale of 1 Å/bin equally spaced in log wavelength and the velocity was derived from the cross-correlation procedure with stellar spectra and galaxy template of known radial velocity obtained the same night, according to Tonry & Davis (1979). In order to test the accuracy of the radial velocities derived from the cross-correlation procedure, using the EVE image analysis package, we have fitted a gaussian profile to the correlation peak displayed; the accuracy of the redshift determination is obtained from the width of the half height of the peak. Table 1 lists positions and heliocentric velocities for 65 individual galaxies in the cluster:

1. Dressler (1980) number
2. alternative name IC or MCG
3. right ascension (hour, min, sec)
4. declination (degree, minute, second)
5. morphological type from Dressler (1980) catalogue
6. estimated total apparent visual magnitude (Dressler, 1980)
7. heliocentric radial velocity with its error in $\mathrm{km\,s^{-1}}$
8. instrumentation and notes, **a** for the 1.50m ESO and **o** for the 3.60m ESO telescopes.

The preparation of the drilled OPTOPUS plates was made by measuring positions of galaxies on the glass copy of the Palomar Sky Survey with the OPTRONICS machine at ESO-Garching, with respect to 20 reference SAO stars. The *rms* error of the polynomial solutions for relative positions is less or equal to 0.3 arcsec. The differences with Dressler (1980) positions are 2 arcsec *rms* with a largest deviation of 6 arcsec. A number appearing in the first column of Table 1 signifies an entry from Dressler's catalogue, in which case the positions are his. All other entries, however, are from the present study.

In order to test the external accuracy of our velocities, we compared our redshift determinations with data available in the literature for the same set of galaxies. Comparisons were made separately for galaxies observed with the ESO 1.50m telescope (V_a) and with OPTOPUS (V_o) (galaxy 69 was not used in the computation, because the discrepancy of the literature determination was greater than 250 $\mathrm{km\,s^{-1}}$): we obtain respectively (13 objects) $< V_a - V_{ref} >=$ 33.8 $\mathrm{km\,s^{-1}}$, the standard deviation in the difference being 59 $\mathrm{km\,s^{-1}}$, and $< V_o - V_{ref} >=$ -14.7 $\mathrm{km\,s^{-1}}$, with $\sigma =$ 91 $\mathrm{km\,s^{-1}}$ (also 13 objects). The comparison between the two observing runs lead to (9 objects): $< V_a - V_o >=$ 3.1 $\mathrm{km\,s^{-1}}$, with $\sigma =$ 61 $\mathrm{km\,s^{-1}}$: all these results are consistent with the errors of Table 1. The velocities in the present study agree with those previously published within a 2 σ level.

3. Discussion

3.1. Velocity analysis

With previous measurements in the same cluster (Proust *et al.* 1987, 1988), and few other data from literature, we obtain for A 151 a total of 65 velocities. The ten galaxies with veloci-

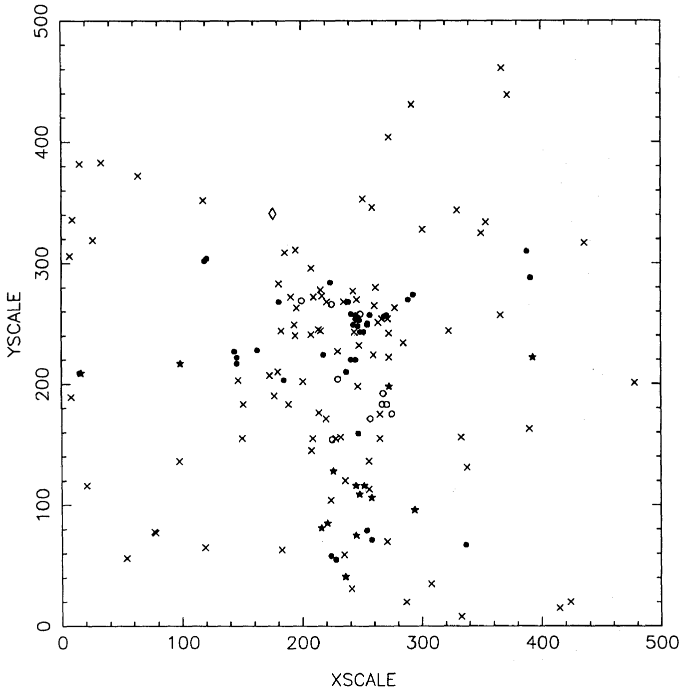

Fig. 1. Galaxy positions of the A 151 cluster symbolized with a circle for objects with $V_r > 20000$ km s^{-1}, filled dot with $14000 \leq V_r < 20000$ km s^{-1}, and filled star with $10000 \leq V_r < 14000$ km s^{-1}; non measured objects are represented with a cross. The foreground galaxy 91 is symbolized with a diamond

ties greater than 20000 km s^{-1} are background objects. During the preparation of the OPTOPUS observations, 158 galaxies were selected after inspection on the Palomar glass plates, considering suitable magnitudes in the central 40' diameter field, approximately (note that galaxy 41 is formed by two distinct objects). Figure 1 shows all the galaxy positions symbolized with a circle for objects with $V_r > 20000$ km s^{-1}, filled dot with $14000 \leq V_r < 20000$ km s^{-1}, and filled star with $10000 \leq V_r < 14000$ km s^{-1}. Non measured objects are represented with a cross; the position of the foreground galaxy 91 is symbolized with a diamond.

Figure 2 shows the velocity wedge diagrams in right ascension, and declination. From figures 1 and 2 one can see the presence of a foreground structure centered on $x_c = 244$ and $y_c = 95$ approximately, in the southern region. Considering that in the 30 arcmin. central region the sampling is fairly homogeneous, we can estimate the cluster center from the density centroid, which gives a position of $x_m = 232$ and $y_m = 229$. The central D galaxy (number 61) is located 5.2 arcmin. from this center.

Figure 3 shows the histogram of radial velocities for the main cluster with a fitted Gaussian centered at the mean velocity $\overline{V} = 16090 \pm 94$ km s^{-1} with a corrected velocity dispersion $\sigma = 587^{+85}_{-61}$ km s^{-1} (confidence level= 68%). The uncertainties were calculated following Danese *et al.* (1980), assuming a mean observational error on individual radial velocities of 100 km s^{-1}. From the standard Friedman cosmology (Mattig 1958) with:

$$D = \frac{c}{H_o q_o^2 (1+z)} \left(q_o z + (q_o - 1)[\sqrt{2q_o z + 1} - 1] \right)$$

we obtain a mean cluster distance of 148 Mpc assuming $H_o = 100$ km s^{-1} Mpc^{-1} and $q_o = 0.1$ and an Abell radius of 35 arcmin. (1.51 Mpc). Note that the D galaxy itself has a velocity differing of only 98 km s^{-1} (0.17 σ) from the mean cluster velocity. All galaxies in the vicinity (20 Kpc) of the D galaxy have a velocity dispersion of 626 km s^{-1}, and thus are members of the overall population. The dynamical mass estimations computed for the 37 galaxies with velocities $14000 \leq V < 20000$ km s^{-1}, as derived from Heisler *et al.* (1985) are listed in Table 2.

Table 2. Dynamical mass estimations

DYNAMICAL MASS ESTIMATION	MAIN CLUSTER ($10^{14} M_\odot$)	SUBSTRUCTURE ($10^{14} M_\odot$)
VIRIAL MASS	2.05	0.28
PROJECTED MASS	5.44	0.36
AVERAGE MASS	4.43	0.28
MEDIAN MASS	3.15	0.40

The foreground structure has a mean velocity of 12229 ± 60 km s^{-1} with a velocity dispersion $\sigma = 217^{+83}_{-49}$ km s^{-1}, corresponding to a distance of 115 Mpc; Table 2 lists the dynamical mass estimations computed for the 10 galaxies situated below $y = 180$ (Figure 1) and having velocities with $10000 \leq V < 14000$ km s^{-1}.

In order to check if the substructure is bound to the main body of the cluster, we have used the procedure devised by Beers *et al.* (1982) which assumes radial orbits. The newtonian criterion for gravitational binding can be stated in terms of the observables as:

$$\frac{V_r^2 R_p}{2GM} \leq \sin^2\alpha \cos\alpha$$

where V_r is the relative velocity along the line of sight of the cluster and its substructure, R_p the projected separation between the cluster and the substructure, M the total mass (cluster + substructure) and α the angle between the cluster and the substructure with the plane of the sky. A necessary condition for bound solutions, is that the left quantity in the above equation must be less than 1. If we adopt $V_r = 3861$ km s^{-1} (16090 − 12229), $M = 4\ 10^{14} M_\odot$ and R_p= 1.047 Mpc (centroid of the cluster) or 1.241 Mpc (centered on the D galaxy) we obtain respectively 4.56 and 5.40 leading to the conclusion that the substructure is not bound to the main cluster. Therefore, it is a projected foreground cluster.

The velocity data show 3 structures, the main cluster at $z = 0.0537$, a foreground group at $z = 0.041$ and a background population at $z \simeq 0.1$. The nearest cluster with known z close to A 151 is A 133 ($z = 0.0604$). No close companions at the same z are apparent within 5 degree of A 151. However, the background galaxies have similar z as A 166 at $z = 0.11$. Moreover, the 4 clusters A 131, A 148, A 157 and A 159 have similar distance class= 5 and similar Abell radii $Ra_o = 0.28$ within 2 degree of the center of A 151. It seems likely that the background grouping belongs to a supercluster at $z = 0.11$–0.12. Within 6 degree, there are three other clusters in this redshift range.

3.2. Wavelet analysis of subclustering

In this section, we present results from the wavelet analysis (Slezak *et al.* 1990, Escalera & Mazure 1991), in order to get the *significance levels* of the substructures (probability P_{wc}).

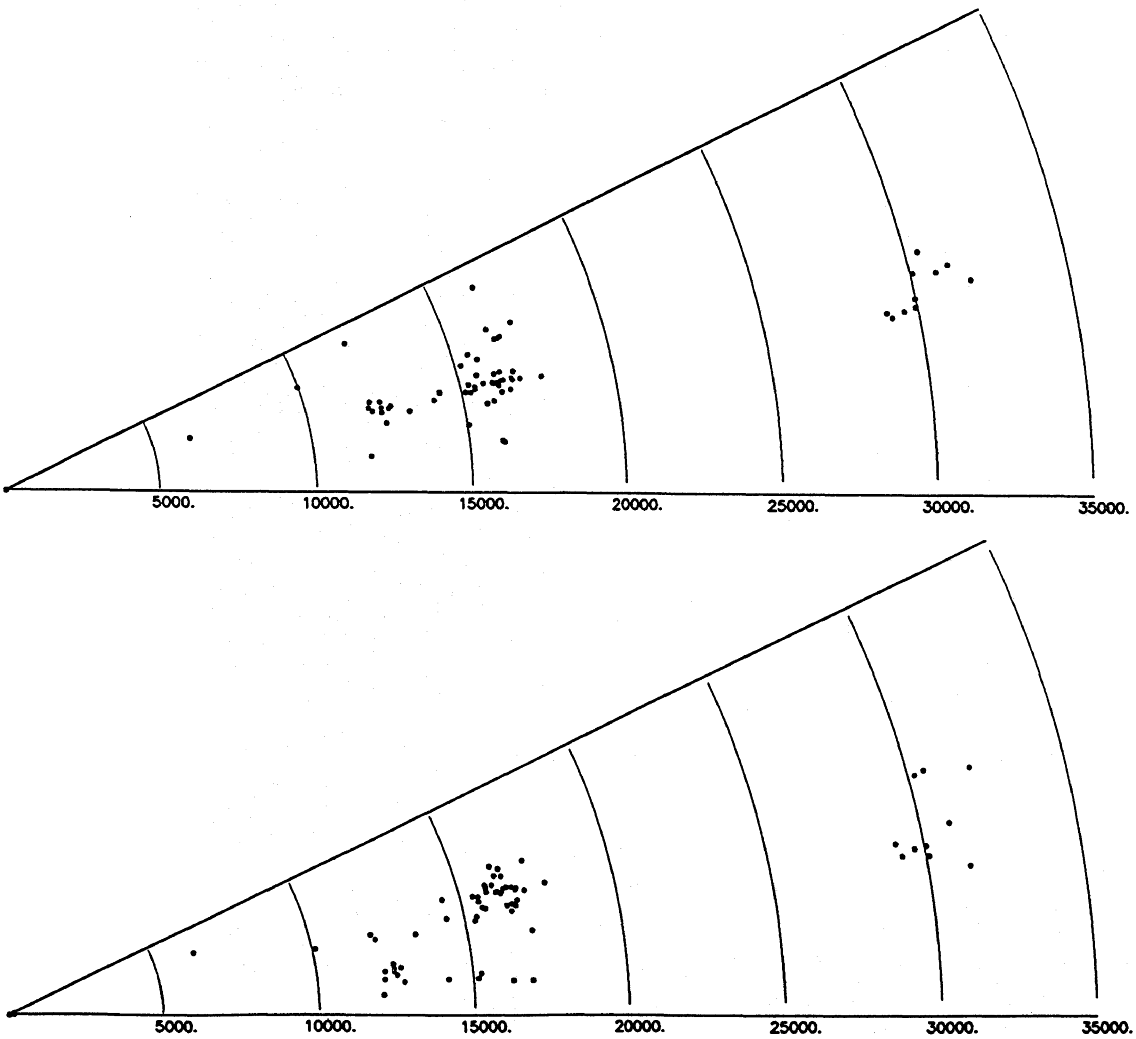

Fig. 2. Wedge velocity diagram in right ascension (up), and declination (down) for the 65 measured galaxies in A 151

All the results were computed using a wavelet scale $\sigma = 0.25$ Mpc on a field of 2 Mpc radius. We used a sample of 52 galaxies from the 65 listed redshifts of the precedent sections, after removing the background objects ($V \geq 20000$ km s^{-1}) as well as the foreground galaxy 91 ($V = 6159$ km s^{-1}). The *significance levels* found with the 2-D data are $P_{wc} \leq 0.001$ for both structures: they are highly significant. We also performed the Percolation test (West *et al.* 1988, Rhee *et al.* 1991), the Mean Harmonic Separation test (M.H.S) (Capelato *et al.* 1980, West *et al.* 1988, Rhee *et al.* 1991), and the Lee statistics (Fitchett & Webster 1987, Rhee *et al.* 1991). Table 4 lists all the corresponding detection results as probabilities of subclustering to be due to random fluctuations.

Figure 4 shows the isosurfaces of the values of the wavelet coefficients through the 3-D analysis. The north and south structures are clearly visible, and the *significance levels* are $P_{wc} \leq 0.001$. The Dressler-Shectman (1988) test leads also to a probability $P \leq 0.001$ that subclustering is due to random fluctuations.

Following the procedure defined by Escalera & Mazure, we list in Table 3 the respective output characteristics of the north and south structures found in A 151. We obtain a relative velocity $V_r = 3752$ km s^{-1} between the two clumps which is very consistent with $V_r = 3861$ km s^{-1} in the previous section. Table 4 summarizes all the above probabilities; the *significance levels* correspond to the south structure.

Table 3. Characteristics of the north and south structure in A 151 from the 3-D wavelet analysis; N is the population, $\overline{V}$ and σ are respectively the mean velocity and dispersion, both expressed in km s^{-1}.

structure	$N_{objects}$	$\overline{V}$	σ
north	22	16017	770
south	8	12265	233

4. Conclusion

In this paper, we have reported new measurements on the A 151 cluster of galaxies. The cluster within the Abell radius of 35 arcmin (1.51 Mpc) is found to be composed of three different redshifts structures: the main cluster at $z = 0.054$, a foreground concentration at $z = 0.041$ and a background population at $z = 0.11$, likely part of a supercluster which includes A 86, A 131, A 157, A 159, A 166, A 183 and possibly others. The 2-D

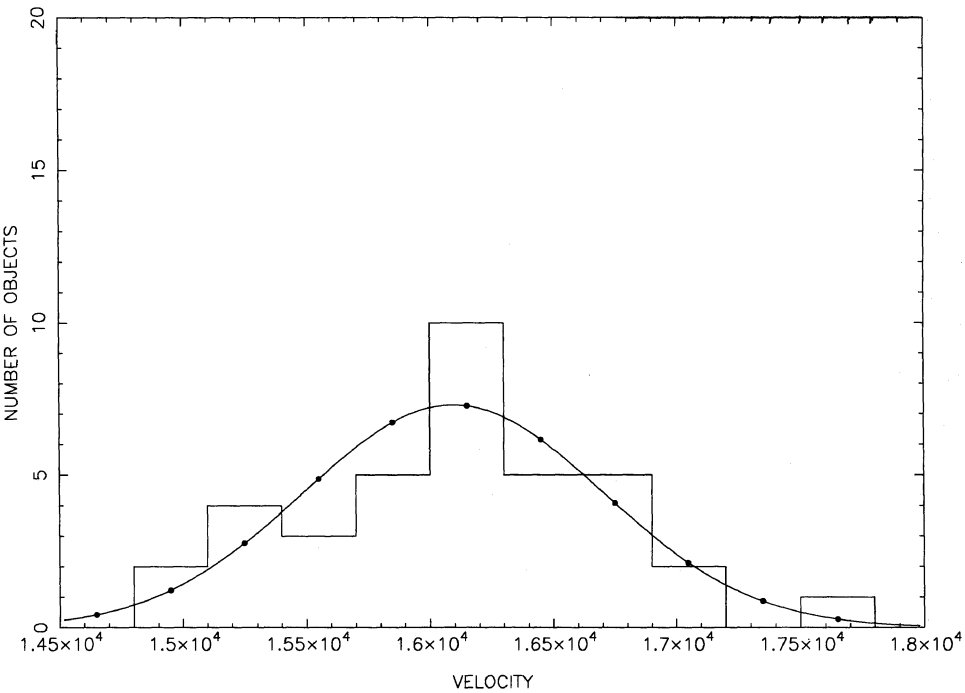

Fig. 3. Histogram of radial velocities for the main cluster in A 151. The fitted Gaussian is centered at the mean velocity $\overline{V} = 16090 \pm 94$ km s^{-1}

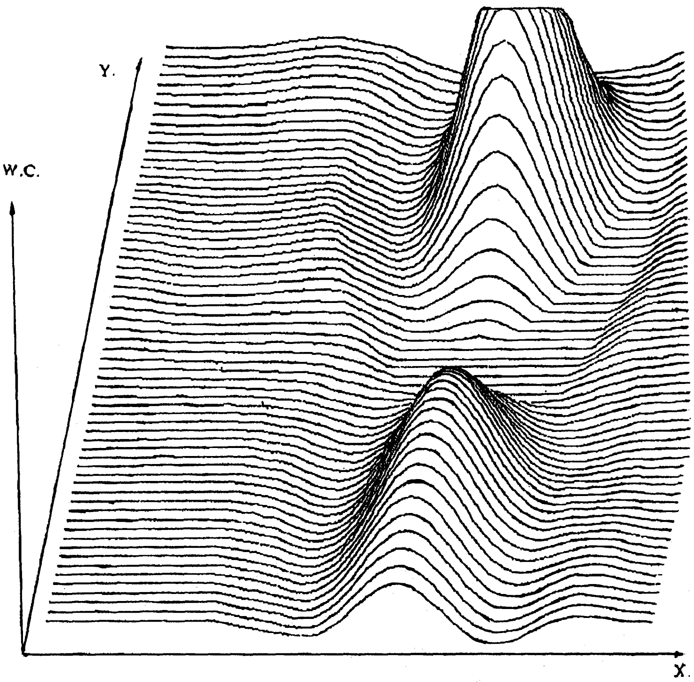

Fig. 4. Isosurfaces of the wavelet coefficients in the weighted 3-D analysis on a grid of 128 × 128 pixels for a wavelet scale a= 32

and 3-D wavelet analyses confirm together with almost all the alternative tests that the south substructure in A151 is relevant, and from the two-body radial orbit method, not bound to the main cluster, thus a foreground group.

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Table 4. Summary of the probability tests; N_{set} is the number of simulations in the computation of probabilities.

TEST	Probability	N_{set}
2-D data		
Percolation	0.880	1000
Lee statistic	0.004	1000
M.H.S.	0.001	1000
Significance Level	≤0.001	1000
3-D data		
Dressler-Shectman	≤0.001	1000
Significance Level	≤0.001	1000

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