STUDY OF THE CORE OF
THE SHAPLEY CONCENTRATION:
I. THE SAMPLE†

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BAP 10–1993–030–DDA

The Monthly Notices of the Royal Astronomical Society, in press.

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ABSTRACT

We report the first results of a spectroscopic survey of galaxies in the core of the Shapley Concentration, the richest nearby supercluster of clusters of galaxies. We have measured 311 new galaxy redshifts in an area of $\sim 4.5$ square degrees centered around the Abell cluster A3558. Considering also the data already available in the literature, the total number of galaxy redshifts in this area amounts to more than 500.

On the basis of these data we estimate the mean velocities and the velocity dispersions of the Abell clusters A3556, A3558 and the poor cluster SC 1329 -314. Finally, from an analysis of the projected and three–dimensional distributions of galaxies in this region, we estimate the galaxy overdensity and find that the core of the Shapley Concentration has an interesting, very complex dynamical state: the main clusters appear to be interacting with each other, forming a single elongated structure containing many subcondensations.

Key words: Galaxies: redshifts; Galaxies: clusters; Large–scale structure.
1. INTRODUCTION

The Shapley Concentration is the most remarkable feature (Scaramella et al. 1989; Vet-tolani et al. 1990) which appears in studying the distribution of the Abell–ACO clusters of galaxies (Abell 1958; Abell, Corwin & Olowin 1989). Zucca et al. (1993) have analyzed, through a percolation algorithm, superclusters of Abell–ACO clusters at various density excesses \( f \) (defined as the ratio between the local and the mean cluster density). They found that at every density contrast the Shapley Concentration stands out as the richest supercluster of the entire sky within a distance of \( 300 \ h^{-1} \ Mpc \) (hereafter \( h = H_0/100 \)); in particular, at \( f \geq 2 \) (which corresponds to a percolation radius of \( \sim 25 \ h^{-1} \ Mpc \)) it has 25 members at a mean distance of \( \sim 140 \ h^{-1} \ Mpc \) contained in a rectangular box of comoving sizes \( \sim 32 \times 55 \times 100 \ h^{-1} \ Mpc \ (\alpha \times \delta \times \text{distance}) \). The central part of this concentration is already evident at high density excesses \( (f \geq 100, \text{corresponding to a percolation radius of } \sim 6 \ h^{-1} \ Mpc) \) and is formed by three condensations: A3528–A3530–A3532, A3571–A3572–A3575 and A3556–A3558–A3560–A3562–A3564–A3566. The three clusters A3556, A3558 and A3562 (with the poor cluster SC 1329 -314 in between A3558 and A3562) form an aligned structure, elongated for \( \sim 3^o \) along the East–West direction and can be considered as the core of the Shapley Concentration.

The Shapley Concentration appears to be very rich and prominent also studying the projected distribution of optical galaxies (Raychaudhury 1989; Raychaudhury et al. 1991) and the spatial distribution of both IRAS galaxies (Allen et al. 1990) and X–ray clusters (Lahav et al. 1989). Indeed, this region contains 6 of the 46 X–ray brightest clusters of the sky at \( |b| > 20^o \) (Edge et al. 1990), \( i.e. \) 13\% of the X–ray brightest clusters reside in only 1.4\% of the sky.

Raychaudhury et al. (1991), assuming that the parameter \( M^* \) of the optical luminosity function of the clusters can be considered a standard candle, concluded that in this region there may be large deviations from the pure Hubble flow. Moreover, on the basis of the available X–ray maps, they noticed that the fraction of multiple clusters in this concentration is more than a factor 5 higher than in the “field”. Both these facts suggest that this supercluster could be dynamically active, in the sense that the processes like cluster evolution due to cluster–cluster or cluster–group merging may be enhanced, as expected in an high density environment.

The Shapley Concentration is also likely to be an important player in explaining the peculiar motion of the Local Group with respect to the Cosmic Microwave Background frame. In fact, Scaramella et al. (1989, 1991) pointed out that this supercluster may be responsible for a significant fraction (\( \lesssim 30\% \)) of the Local Group peculiar motion, adding its dynamical pull to that from a closer overdensity of galaxies at \( \sim 40 \ h^{-1} \ Mpc \). The latter overdensity of galaxies, dubbed “Great Attractor”, was suggested to be a major source of the Local
Group acceleration (Lynden-Bell et al. 1988; Lynden-Bell, Lahav & Burstein 1989; Faber & Burstein 1988; Dressler 1988). The suggestions of Scaramella et al. (1989, 1991), on the contrary, would imply a significantly larger coherence scale for the peculiar velocity flow, a fact which seems to be supported by recent findings (Willick 1990; Mathewson, Ford & Buchhorn 1992). Also, Tully et al. (1992) suggested that these two “attractors” could be part of a single elongated planar structure, extending for \( \sim 450 h^{-1} \) Mpc.

The aim of this work is the study of the core of the Shapley Concentration, with particular attention to the possible physical connection, made by inter–cluster galaxies, between the main clusters. In Sect. 2 we present the sample and the new redshift data; in Sect. 3 we discuss the projected and three–dimensional distribution of the galaxies and in Sect. 4 we describe the methods we used to determine the mean velocity and the velocity dispersion of the clusters and we apply them to each cluster. Finally, in Sect. 5 we summarize our results.

2. THE SAMPLE

2.1 The galaxy catalogue

The photometric data catalogue is the COSMOS/UKST galaxy catalogue of the southern sky (Yentis et al. 1992) obtained from the automated scans of the UKST–J plates by the COSMOS machine. The core of the Shapley Concentration, as defined in Sect. 1, is completely contained in the plate \( \# 444 \), where 13600 galaxies are listed with \( b_J \leq 20 \). The catalogue lists, for each galaxy, accurate coordinates (\( \alpha(2000) \) and \( \delta(2000) \)), the \( b_J \) magnitude, the major diameter (in arcmin), the area in pixels of the object, the ellipticity and the position angle. From the catalogue of plate 444 we have extracted a sub–sample of about \( 3^{\circ}.2 \times 1^{\circ}.4 \) with \( 13^{h}22^{m}06^{s} < \alpha < 13^{h}37^{m}15^{s} \) and \( -32^o22'40'' < \delta < -30^o59'30'' \), which contains the complex \( A3556–A3558–A3562 \). Fig. 1a shows isodensity contours for the galaxies with \( b_J \leq 19.5 \) in this area (2241 galaxies). Here we have chosen 19.5 as the limiting magnitude for the contours since in our spectroscopic work (see Sect. 2.2 and 2.3) we have not observed galaxies fainter than this limit. The three Abell clusters \( A3558, A3556 \) and \( A3562 \) are clearly visible in this figure, as well as the poor cluster \( SC 1329-314 \).

In order to obtain three–dimensional information for the galaxy distribution in this area, we had originally planned to cover it with a number of OPTOPUS fields (Fig. 1b), whose centers are listed in column (2) and (3) of Table 1, together with the observation date, in column (4). Three of these fields (\( \# 1, 4, 5 \)) were planned to be observed twice, because of their high density of galaxies. Unfortunately, observations of field \( \# 1 \) completely failed, for both technical and meteorological problems.

2.2 Observations and data reduction

Spectroscopic observations were obtained at the ESO 3.6 m telescope in La Silla, equipped with the OPTOPUS multifiber spectrograph (Lund 1986), in the nights of 9–10–11 March 1991 and 25 April 1992. The OPTOPUS multifiber spectrograph uses bundles of 50 optical
fibers, which can be set within the field of the Cassegrain focal plane of the telescope; this field has a diameter of 32 arcmin, and each fiber has a projected size on the sky of 2.5 arcsec. We used the ESO grating # 15 (300 lines/mm and blaze angle of 4°18′) allowing a dispersion of 174 Å/mm in the wavelength range from 3700 to 6024 Å. The detector was the Tektronic 512 × 512 CCD with a pixel size of 27 µm corresponding to 4.5 Å, i.e. a velocity bin of \( \sim 270 \text{ km/s} \) at 5000 Å. We dedicated 5 fibers to sky measurements, remaining with 45 fibers available for the objects. An average of about 3 spectra were lost in each exposure, due to broken or badly connected fibers.

The observing time for each field was one hour, split into two half–hour exposures in order to minimize the effects due to the “cosmic” hits. The observing sequence was: a 30 second exposure of a quartz–halogen white lamp, a 60 second exposure of the Phillips Helium arc, then the first and the second field exposures, and again the arc and the white lamp.

The extraction of the one–dimensional spectra has been made using the APEXTRACT package as implemented in IRAF\(^{(1)}\). The loci of the spectra were individuated and followed along the wavelength direction in the white lamp frames and the solutions were used to find and extract the arcs and the galaxy spectra.

The subtraction of the sky is the most critical step of the multifiber data reduction, because it is impossible to separate sky and object in the same spectrum (as instead done in the slit spectroscopy). Moreover, the transmission of the light varies from fiber to fiber and therefore it is not possible the direct subtraction of a sky spectrum obtained with a fiber from a galaxy spectrum obtained with another fiber. In order to estimate the transmission of each fiber we adopted the following procedure. For each exposure, we fitted a Gaussian profile to the [OI] \( \lambda 5577 \) sky line in each spectrum of the field and computed the continuum–subtracted flux of this line. Under the assumption that the flux and the shape of the spectrum of the night sky do not appreciably vary inside the telescope field (this is true on scales of \( \sim \) degree, see also Wyse & Gilmore 1992), this flux should have the same value for all the spectra, apart from a multiplicative factor, which is the transmission of each fiber. In this way we could obtain an estimate of the relative transmission of each fiber.

In order to reveal possible contamination of the calibrating sky line by “cosmic” hits, we computed also the mean and the dispersion of the ratios between the peak of the continuum–subtracted counts of the [O I] \( \lambda 5577 \) line and the same quantity in the Na \( \lambda 5891 \) sky line: values of this ratio \( 3 \sigma \) above the mean have been taken to be indicative of the presence of a “cosmic” hit in the [O I] \( \lambda 5577 \) line. However this contamination happened rarely and in all cases the presence of the “cosmic” hit was clearly seen in a visual inspection of the spectra. In these cases we eliminated the contamination by fitting the line below the spike.

\(^{(1)}\) IRAF is distributed by KPNO, NOAO, operated by the AURA, Inc., for the National Science Foundation.
After normalization for the relative fiber transmission, the 5 sky spectra were averaged and subtracted from the object spectra. The comparison of the two exposures of the same field revealed other “cosmic” spikes affecting the spectra, which were eliminated by interpolating the continuum on both sides of the spikes.

Radial velocities of galaxies whose spectra are dominated by absorption features have been determined using the program XCSAO of the IRAF task RVSAO, written by Kurtz et al. (1992) following the cross-correlation method of Tonry & Davis (1979). After having fitted and subtracted the continuum, we filtered the spectra as suggested by Tonry & Davis: low frequency cut-off at the frequency 5, high frequency cut-off at 250 and full transmission between 20 and 125. In determining the maximum value of the cross-correlation function we fit the main peak above half maximum with a parabola. As templates for the determination of the radial velocities we used the spectra (kindly provided by L. Guzzo) of 6 galaxies, whose velocities have high quality measurements in the literature. Then, the “best” velocity has been selected on the basis of the minimum cross-correlation error rather than the maximum $R$ parameter of Tonry & Davis (1979). Indeed, being $R$ the ratio between the height of the correlation peak and the r.m.s. of the antisymmetric part of the correlation function, the choice of the maximum $R$ does not take into account the possible presence of very wide symmetrical peaks. On the contrary, the errors, as calculated by Kurtz et al. (1992), contain the FWHM of the peaks, called $w$, as

$$\text{error} = \frac{3}{8} \frac{w}{(1 + R)}$$

Finally, for spectra with strong emission line features we have used the EMSAO program of the same IRAF task RVSAO.

### 2.3 Redshift data

We have obtained a total of 383 spectra: 58 spectra ($\sim 15\%$) were not useful for redshift determination because of poor signal-to-noise ratio, 14 objects ($\sim 4\%$ of the total number of spectra) turned out to be stars, leaving us with 311 galaxy redshifts. The median error on these velocities is $\sim 58 \text{ km/s}$.

The galaxies of each observed field are given in Table 2, sorted by decreasing magnitude. Column (1) gives the identification number, column (2), (3) and (4) list the right ascension, the declination and the $b_J$ magnitude, respectively. Column (5) and (6) give the heliocentric velocity ($v = cz$) and its internal (i.e. cross-correlation) error; a blank in column (5) means that the object was observed but it was impossible to derive velocity information from its spectrum, while “star” indicates those objects which turned out to be stars (after the spectrum analysis). Finally, column (7) marks with the code $EMISS$ the redshifts determined from emission lines.

In Plates 1–8 we show the finding charts for all galaxies we observed.
Our sample of spectroscopic data does not contain any galaxy with already published velocities. There are, however, 45 galaxies in common with those observed by Stein et al. (private communication). Being these two sets of data taken with the same instrument but reduced and cross-correlated with different packages (IRAF vs MIDAS), a direct comparison of the velocities gives a rough estimate of the external errors in the data. We have compared our velocities \( v_{us} \) with those of Stein et al. \( v_{Stein} \), taking into account the errors \( \text{err}_{us} \) and \( \text{err}_{Stein} \). Computing the mean and the r.m.s. of the variable

\[
\frac{v_{Stein} - v_{us}}{\sqrt{\text{err}_{Stein}^2 + \text{err}_{us}^2}}
\]

we obtain \( \text{mean} = 0.23 \pm 0.28 \) and \( \text{r.m.s.} = 1.87 \), to be compared with the expected values of 0 and 1, respectively. The resulting mean shows that the two sets of measurements are consistent with having the same velocity zero point, while the value of the r.m.s. has a probability lower than 0.001 (through a \( \chi^2 \) test) to be compatible with the value 1. Thus, assuming that for both sets of data the quoted errors are good estimates of the cross-correlation errors, the value of the r.m.s. suggests that the true statistical errors are on average 1.87 times greater than the cross-correlation ones. This result is consistent with a similar analysis performed by Malumuth et al. (1992): using multiple observations of 42 galaxies, reduced in the same way, they concluded that this factor is of the order of 1.6.

Adding to our data additional redshifts available in the literature, the total number of redshifts in the area shown in Fig. 1 is 511, 200 of which are taken from the literature and 311 are new measurements.

3. VELOCITY DISTRIBUTION AND OVERDENSITY

Fig. 2 shows velocity versus apparent magnitude for all the galaxies with measured redshifts in our sample. In addition to the extremely prominent structure at \( v \sim 15000 \ km/s \), other clumps of galaxies at \( v \sim 25000 \), 40000 and 55000 km/s are visible, separated by “voids” of typical size of \( \sim 5000 \ km/s \). In the foreground of the Shapley Concentration there are a few galaxies with \( v \sim 4000 \ km/s \), consistent with the velocity of the Great Attractor.

The significance of these voids and peaks is not easy to be determined, because no well-defined magnitude completeness limit can be determined for our spectroscopic data. Table 3 shows, as a function of magnitude, the total number of objects in the photometric catalogue, the number of galaxies with measured redshift (including also literature data), the number of stars and the percentage of spectroscopic data in the area covered by our OPTOPUS fields. As it is clear from the last column of the table, the completeness of our spectroscopic data is smoothly decreasing with magnitude, from \( \sim 75\% \) for the brightest galaxies down to \( \sim 15\% \) for the faintest galaxies in the sample.

From these data we have estimated the expected distribution of uniformly distributed galaxies by integrating a luminosity function with parameters \( \alpha = -1.10 \) and \( M^* = -19.67 + \)
5 log $h$ (Vettolani et al. 1993) and weighting the expected number of galaxies in each magnitude bin by the corresponding spectroscopic completeness. The normalization has been adjusted in such a way as to reproduce the observed number of galaxies outside the velocity range of the Shapley Concentration. To this purpose we have adopted the velocity intervals $v < 11000 \text{ km/s}$ and $v > 18000 \text{ km/s}$. We have also verified that the integration of the luminosity function with the here adopted normalization reproduces reasonably well the counts of galaxies with $b_J \lesssim 19.5$ (Heydon–Dumbleton, Collins & MacGillivray 1989). Fig. 3a shows the histogram of the observed velocities (in bins of 1000 km/s) and the resulting expected distribution. Note that, in order to visualize the distribution outside the Shapley Concentration, the Y–axis has been cut at $N = 20$, while the bin $14000 < v < 15000 \text{ km/s}$ contains 166 galaxies.

This histogram suggests the possible presence of a void of about 4000 km/s just behind the main peak. No galaxy is seen in the velocity range 18000 – 22000 km/s, where $\sim 10$ galaxies would be expected on the basis of a uniform distribution. Other possible voids, with approximately similar statistical significance, are seen in the velocity ranges 28000 – 34000 km/s and 44000 – 51000 km/s.

Fig. 3b shows a close–up of the distribution of the observed velocities in the range 10000 – 20000 km/s; note that the velocity bin here is 500 km/s. The average velocity is 14248 km/s, with a Gaussian velocity dispersion of 1083 km/s: these are the parameters of the Gaussian curve superimposed on the velocity distribution.

To estimate the overdensity of galaxies in this area is not straightforward, because the observed velocity distribution is the convolution of the distance distribution with the velocity dispersion within the clusters. As such, we can not unambiguously compute the depth distribution of the galaxies. The total number of galaxies in the velocity range 11000 – 18000 km/s is 430, to be compared with an expected number of $\sim 15$, on the basis of a uniform distribution. This would correspond to an overdensity $(N - N_{\text{exp}})/N_{\text{exp}} \simeq 28$, over a depth of 70 $h^{-1}$ Mpc. Therefore, this estimate is a lower limit to the real spatial overdensity of the bulk of the galaxies in this region.

A second, more stringent, lower limit to the overdensity for the clusters in the core of the Shapley Concentration can be obtained by comparing the number of galaxies within $\pm 1\sigma$ from the average velocity ($N = 304$) with the expected number of galaxies within the same velocity range ($N_{\text{exp}} \sim 5$). From this we derive an estimate of an overdensity of $\sim 65$ over a depth of $\sim 20$ $h^{-1}$ Mpc.

It is important to note here that these overdensities have been estimated with respect to an assumed uniform background and do not take into account the possibility that the area analyzed here is the peak of a much more extended overdensity, not simply associated to Abell clusters. That this might be the case is shown in Fig. 4, which represents the
ratio between the differential galaxy counts as a function of magnitude for the whole plate 444 with respect to those of a reference area in a region of \( \sim 140 \) square degrees, near the South Galactic Pole (filled circles). Open circles show the same ratio after excluding all the galaxies within 1 Abell radius of the 5 Abell clusters of the Shapley Concentration lying in this plate (Zucca et al. 1993). At each magnitude the surface density of galaxies in plate 444 is significantly higher than in the reference area, even after excluding the cluster galaxies. In particular, the observed surface density of inter–cluster galaxies is about twice that the reference area at \( b_J \sim 16.2 \), corresponding to \( M^* \) galaxies at a distance of \( \sim 140 \ h^{-1} \ Mpc \).

A more detailed study of the velocity distribution and the spatial overdensity of all galaxies with \( b_J \leq 16.5 \) in the entire plate 444 is in progress (Schuecker et al., in preparation).

In Fig. 5 we show the wedge diagram of the galaxies of our sample in the velocity range 10000 – 24000 \( \text{km/s} \). The three pairs of straight lines (solid, dashed and dotted) show the projection in right ascension of 1 Abell radius for the three clusters A3562, A3558 and A3556, respectively. Apart from the “hole” due to the lack of data in the area of the failed field #1, centered on the cluster A3562, the galaxy distribution seems to form a single connected structure. However, the mean velocity of A3562 as reported by Melnick & Moles (1987), 15060 \( \text{km/s} \), suggests a continuity also across the failed field. The main features in this figure are:

a) the “Fingers of God” visible at the center of the two clusters A3558 and A3556;

b) two groups of galaxies, clearly separated in velocity, at about \( v \sim 14400 \ \text{km/s} \) and \( v \sim 12200 \ \text{km/s} \) eastward of A3562;

c) two possibly separated groups at \( v \sim 13500 \ \text{km/s} \) and \( v \sim 15000 \ \text{km/s} \) at \( \alpha \sim 13^{h}30^{m} \), corresponding to about 1 Abell radius from both A3558 and A3562 (see also the discussion below). Note that this right ascension corresponds to the approximate position of the density enhancement identified with the poor cluster \( SC \ 1329-314 \);

d) a zone devoid of galaxies just behind the main structure, extending radially from 17250 to 22000 \( \text{km/s} \) (see the discussion above in this section).

In order to better understand how these features are related to the projected distribution of galaxies, we have superimposed the galaxies with redshift information to isodensity contour maps of the region. Fig. 6 shows the most interesting part of these plots, centered on A3558: panel (a) refers to all galaxies with \( b_J \leq 19.5 \), while panels (b), (c) and (d) show the isodensity contours for galaxies with \( b_J \leq 18 \), \( 18 < b_J \leq 19 \) and \( 19 < b_J \leq 19.5 \), respectively. The isodensity levels have been chosen as integer multiple of the mean number of galaxies per pixel in the entire plate (the values for each panel are given in the figure captions). The size of the superimposed dots is inversely proportional to the velocity of the galaxies. The main features of Fig. 6a are the density peak of A3558 (in the center) extending on the East toward the poor cluster \( SC \ 1329-314 \) and the overdensity corresponding to A3556 on the
West: note that $A3558$ and $A3556$ appear to be unconnected only due to our choice of the lower isodensity value. $A3558$ appears to be elongated with the major axis at a position angle of $\sim 135^\circ$ (measured from North toward East): such a departure from circular symmetry, with a similar position angle, is seen also in ROSAT X–ray maps of this cluster (Bardelli et al., in preparation).

Fig. 6a is also characterized by a number of smaller substructures: in particular it is clear the presence of two subcondensations (arrowed in the figure) at different velocities at the approximate position of the poor cluster $SC~1329$ -314 (see Sect.4.3). Galaxies in the subcondensation $A$ have, on average, smaller velocity (higher fraction of big dots) than galaxies in the subcondensation $B$. The galaxies in these two clumps appear to have also a different magnitude distribution. While subcondensation $A$ is clearly visible on the contour plot at brighter magnitude, the opposite is true for subcondensation $B$. This effect would be expected if $B$ were at a significantly larger distance than $A$, contrary to what is suggested by the velocity data ($\Delta v \sim 750$ km/s, see Sect.4.3). The conclusion would be that either the galaxies in the two subcondensations have quite different luminosity function or there are strong peculiar motions which can alter significantly the correspondence between velocity and distance. An other interesting feature which is clearly seen in the maps of Fig. 6 is the decrease with magnitude of the contrast between the surface density of the center of $A3558$ and the average density over the entire plate. While this contrast is $\sim 15$ for galaxies with $b_J \leq 18$, it decreases to $\sim 3$ for galaxies with $19 < b_J < 19.5$. In the latter magnitude range the center of $A3558$ is not more conspicuous than subcondensation $B$.

The presence of these substructures makes the dynamical situation of this region quite complex. For this reason, the estimate of the masses of these clusters is not straightforward and needs a careful analysis of the contribution of the various subcondensations: estimates for the masses, the luminosity functions and the mass–to–light ratios for these clusters will appear elsewhere (Bardelli et al., in preparation).

4. MEAN VELOCITY AND VELOCITY DISPERSION

OF THE CLUSTERS

In order to estimate the mean velocity and the velocity dispersion for the three clusters $A3558$, $A3556$ and $SC~1329$ -314 we have used the biweight location ($C_{BI}$) and scale ($S_{BI}$) estimators discussed by Beers, Flynn & Gebhardt (1990) and already adopted for the study of $A3558$ by Teague, Carter & Gray (1990). These estimators are defined as:

$$C_{BI} = m + \frac{\sum_{|u_i|<1}(v_i - m)(1 - u_i^2)^2}{\sum_{|u_i|<1}(1 - u_i^2)^2}$$ (3)

$$S_{BI} = \sqrt{N} \left[ \frac{\sum_{|u_i|<1} (v_i - m)^2 (1 - u_i^2)^4}{|\sum_{|u_i|<1}(1 - u_i^2)(1 - 5u_i^2)|} \right]^{1/2}$$ (4)
\[ u_i = \frac{v_i - m}{c \cdot \text{median}(|v_i - m|)} \]

where \( m \) is the median of the data, \( \text{median}(|v_i - m|) \) is the median value of the variable \(|v_i - m|\) and the “tuning constant” \( c \), following Beers et al., has been set equal to 6.0 for the location estimator and equal to 9.0 for the scale estimator. The physical meaning of these estimators is analogous to that of the mean \(<v>\) and the standard deviation \((\sigma_v)\), to which they asymptotically approach when the sample is taken from a Gaussian distribution, but they are proved to be more robust and resistant than the classical estimators (Beers et al. 1990).

These estimators are characterized by a cut–off on the data tails corresponding, for a Gaussian distribution, to \( \sim 4\sigma \) for \( CB1 \) and to \( \sim 6\sigma \) for \( SBI \) and a decreasing weight to the most extreme data. In order to calculate these quantities, we have used the program ROSTAT, kindly given us by T. Beers; the errors are the 68\% uncertainties computed after one hundred bootstrap resampling of the data.

In order to find the velocity range in which the cluster members lie, we have assumed that the velocity distribution of cluster galaxies is Gaussian, as expected when the system has undergone a violent relaxation. In order to individuate this velocity range, we have applied the following iterative procedure. First, we have computed \( CB1 \) and \( SBI \) using all galaxies, without limits in velocity, and we have checked the Gaussianity. In order to check the hypothesis of Gaussianity, we performed 4 standard tests: the \( a \) test (defined as the ratio between the mean deviation and the standard deviation), the \( b_1 \) (skewness) test, the \( b_2 \) (kurtosis) test and the \( I \) test (the ratio between the standard deviation estimator and the biweight scale estimator). The definitions and the percentage points for \( a \), \( b_1 \) and \( b_2 \) are reported in Pearson & Hartley (1962), while the \( I \) test and the formulae to calculate the critical points are reported by Teague et al. (1990). If one or more tests rejected the null hypothesis of Gaussianity, following a suggestion in Beers et al. (1990) we have repeated the analysis using the velocity range \( CB1 \pm 6 \cdot \text{median}(|v_i - m|) \) and we have checked again the Gaussianity of the new velocity distribution. We have iterated this procedure until the velocity distribution of galaxies was consistent with being Gaussian at more than 5\% probability level for all the four tests. In all cases convergence has been reached in a few iterations.

The velocity histograms for the three clusters are shown in the three panels of Fig. 7, where the adopted radii are 36 arcmin (= 1 Abell radius) for A3558, 18 arcmin for A3556 and 6 arcmin centered at the positions of the two subcondensations \( A \) and \( B \) (see previous section) for \( SC 1329 -314 \). In the last panel the dashed histogram refers to subcondensation \( A \), while the solid one refers to subcondensation \( B \).

4.1 Abell 3558

A3558, also known as Shapley 8 or \( SC 1325 -311 \), is the richest cluster contained in the
ACO catalogue, the only one with richness class 4. It is dominated by a central giant galaxy and it is a strong X–ray emitting cluster with an estimated luminosity of $8.7 \times 10^{44}$ ergs/s, in the energy range $[2 - 10]$ keV (Day et al. 1991). Moreover, this object is also interesting because Gebhardt & Beers (1991) found that it is one of the 4 clusters which are claimed to present a statistically significant discrepancy (at 90% level) between the velocity of the centroid of the redshifts and the velocity of the dominant galaxy.

Within a circle of 1 Abell radius ($\sim 1.5 \ h^{-1} \text{Mpc}$) around this cluster we have 267 galaxies with measured redshifts in the velocity range $10260 - 18516 \ \text{km/s}$ (chosen following the iterative procedure described in the previous section), out of which $\sim 100$ are taken from Metcalfe, Godwin & Spenser (1987) and Teague et al. (1990); the velocity histogram of these galaxies is shown in Fig. 7a. Because of the large number of redshift data now available we have divided the total sample in 6 sub–samples at different distances from the center and have analyzed them separately. Table 4 lists the main properties of these sub–samples. Column (1) and (2) give the distance from the center in arcsec and $h^{-1} \ \text{Mpc}$ respectively, column (3) and (4) list the number of galaxies in our bi–dimensional sample and the number of measured redshifts in the velocity range $10260 - 18516 \ \text{km/s}$.

In order to better understand the contribution to $C_{BI}$ and $S_{BI}$ from the galaxies at different distances from the cluster center, we have analyzed not only the “integral” sub–samples described above, but also “differential” sub–samples, selected as annuli around the cluster center, with distances in the ranges $0 - 360$, $360 - 718$, $718 - 1077$, $1077 - 1435$, $1435 - 1794$ and $1794 - 2155 \ \text{arcsec}$, respectively. The four panels of Fig. 8 show the mean velocity and the velocity dispersion for the integral (panels a and c) and the differential (panels b and d) sub–samples, whose values are reported in Table 5. The $C_{BI}$ and $S_{BI}$ derived for the integral sub–samples are approximately constant up to half an Abell radius, and in good agreement with previous estimates: indeed, we find (for the third sub–sample) $C_{BI} = 14242 \pm 80 \ \text{km/s}$ and $S_{BI} = 986 \pm 60 \ \text{km/s}$, while Metcalfe et al. (1987) report $< v > = 14237 \ \text{km/s}$ and $\sigma = 991\pm157 \ \text{km/s}$ and Teague et al. (1990) give $< v > = 14233 \ \text{km/s}$ and $\sigma = 1002 \ \text{km/s}$.

However, there is a tendency for $C_{BI}$ to increase at larger distances from the center: this feature is very clear for the differential sub–samples (Fig. 8b), where there is a significant discontinuity between the third and the fourth sub–samples. This behaviour is probably a consequence of the fact that, as the distance from the center increases, the contamination by galaxies belonging to subcondensation B of the poor cluster $SC \ 1329 -314$ becomes higher. The distribution of $S_{BI}$ in the differential sub–samples (Fig. 8d) does not show any statistically significant trend.

As already mentioned above, Gebhardt & Beers (1991) noticed that $A3558$ (and other three clusters) presents a significant offset between the mean velocity of the cluster and the
velocity of the dominant galaxy \((v_D = 14037 \pm 21; \text{Teague et al. 1990})\). Our data, taken at face value, seems to confirm such a discrepancy. In fact, limiting ourselves at the first three integral sub–samples, we find that the difference between \(C_{BI}\) and \(v_D\) is significant at \(\sim 1.6\), 1.8 and 2.5 \(\sigma_D\) level respectively, where

\[
\sigma_D = \frac{|C_{BI} - v_D|}{\sqrt{err_{C_{BI}}^2 + err_{v_D}^2}}
\]  

(6)

The trend of increasing significance with increasing distance from the center is not due to changes of \(C_{BI}\), but rather to the decrease of \(err_{C_{BI}}\) when more galaxies are included in the sample. However, in the light of the possibility that the contamination on \(C_{BI}\) from different subcondensations might not be negligible, even in the inner region of the cluster, we have repeated the same analysis by dividing each sub–sample in two parts, eastward and westward of the center. The result is that the mean velocities of the three West sub–samples are all inconsistent with \(v_D\) at more than 2\(\sigma_D\) level, while the discrepancy is reduced to 0.28, 0.03, 0.93 \(\sigma_D\) for the first three East sub–samples. This result suggests that the observed discrepancy between \(C_{BI}\) and \(v_D\) is at least partly, if not completely, due to asymmetries in the velocity distribution of the galaxies in the cluster.

### 4.2 Abell 3556

\(A3556\) is an ACO cluster of richness class 0 and Bautz–Morgan type I. Its angular distance from \(A3558\) is only \(\sim 50\) arcmin and there is an overlap between the Abell radii of these two clusters (see Fig. 1a). For this reason, we have analyzed for this cluster the velocity distribution of the galaxies within half an Abell radius and in the velocity range \(11293 - 17509\) \(km/s\), chosen following the Gaussianity criterion (see Fig. 7b). From this sample of 48 galaxies we obtain \(C_{BI} = 14407 \pm 89\) \(km/s\) and \(S_{BI} = 554 \pm 47\) \(km/s\). The average velocity \(C_{BI}\) of \(A3556\) is therefore consistent (at 1.4\(\sigma\) level) with that of \(A3558\).

### 4.3 The poor cluster SC 1329 -314

The poor clusters \(SC 1329 -314\) is in between \(A3558\) and \(A3562\). On the basis of 11 redshifts, Melnick & Moles (1987) derived for this cluster a mean velocity of 13300 \(km/s\) and a velocity dispersion of 1050 \(km/s\), but they do not give the positions of their measured galaxies. As discussed above, our data suggest the presence of at least two possibly separated subcondensations in this area. We have determined \(C_{BI}\) and \(S_{BI}\) separately in these two substructures, using all galaxies within 6 arcmin around tentative center positions estimated from the surface density contour plot. We found \(C_{BI}(A) = 14074 \pm 249\) \(km/s\) and \(S_{BI}(A) = 1044 \pm 96\) \(km/s\) for the 28 galaxies in \(A\) and \(C_{BI}(B) = 14828 \pm 225\) \(km/s\) and \(S_{BI}(B) = 676 \pm 189\) \(km/s\) for the 14 galaxies in \(B\) (see Fig. 7c). Subcondensation \(A\) consists of brighter galaxies (see Fig. 6b) and is closer than \(B\) to the nominal center of the cluster: therefore it is likely that Melnick & Moles (1987) measured galaxies mainly in this group, thus obtaining a lower value for the mean velocity.
Finally, we note the presence of two peaks of X–ray emission probably associated with these subcondensations. In our ROSAT PSPC image pointed on A3558 it is present, in addition to the cluster, a secondary peak of X–ray emission at a distance of a few arcminutes from subcondensation B, and another peak in an image taken by the Einstein Observatory (as reported by Raychaudhury et al. 1991) is very near to subcondensation A. This correspondence seems to confirm the physical reality of these two associations of galaxies.

5. SUMMARY

In this paper we presented and discussed a sample of galaxies in the core of the Shapley Concentration, formed by \( \sim 500 \) galaxy redshifts (311 of which are new measurements) in a region of the sky included in a rectangle of \( \sim 3^{\circ}.2 \times 1^{\circ}.4 \). The new redshifts were obtained with multifiber spectroscopy and the median error on the velocities is \( \sim 58 \) km/s.

From an analysis of the spatial distribution of this sample, combined with the bi–dimensional isodensity contours of the COSMOS/UKST catalogue, we conclude that the core of the Shapley Concentration is in a complex dynamical state. The three main clusters of this region (A3558, A3556 and A3562) are each other interacting and form a single elongated structure, orthogonal to the line of sight, with many subcondensations. In particular, we have studied two subcondensations around the position of the poor cluster SC 1329-314, which is in between A3558 and A3562. These substructures are probably real groups of galaxies, subjected to the gravitational fields of the main clusters.

The galaxy overdensity in this area, estimated with respect to an average uniform background, is \( \gtrsim 65 \). Being a lower limit, this number is consistent with the overdensity of the order of 110 \( \pm 40 \) found by Postman et al. (1988) for the galaxies in the clusters of the Corona Borealis supercluster. From an analysis of the galaxy counts in the whole plate 444 we conclude that such an overdensity is present, although at a much lower level, also for inter–cluster galaxies over a much larger area.

Furthermore, we have derived the mean velocity and the velocity dispersion for A3558, A3556 and SC 1329-314, using the biweight estimator of the location and scale. In particular, for A3558 we have calculated these quantities as a function of the distance from the cluster center, concluding that also in deriving these parameters the contamination from the subcondensations is not negligible, especially at distances greater than 0.5 Abell radii.

From this analysis it is clear that the core of the Shapley Concentration is dynamically very active; therefore it is very interesting to derive the masses and the mass–to–light ratios of these clusters, as well as the luminosity function of the galaxies, in order to estimate the time scale of their merging. We will present elsewhere (Bardelli et al., in preparation) the results of this dynamical analysis.
Acknowledgements:
We warmly thank Paul Stein for having allowed us the use of his redshifts in advance of the publication, T.C. Beers for having kindly given us his program ROSTAT, Luigi Guzzo for the template spectra and R.Primavera for the photographic artwork. This work has been partially supported by the Italian Space Agency (ASI) under the contract ASI 91–RS–86.
FIGURE CAPTIONS

Figure 1:

a) Isodensity contours of the core of the Shapley Concentration in an area of $\sim 3^\circ.2 \times 1^\circ.4$. The figure refers to galaxies with $b_J \leq 19.5$ and binned in $2\ arcmin \times 2\ arcmin$ bins; the data have been smoothed with a Gaussian with a FWHM of $6\ arcmin$. For the three Abell clusters circles of one Abell radius have been drawn (dashed curves); the poor cluster $SC\ 1329-314$ is the peak between the clusters $A3558$ and $A3562$.

b) Same as Fig. 1a, with superimposed the nine OPTOPUS fields observed in March 1991 and April 1992.

Figure 2:

Velocity versus apparent magnitude for all the galaxies with measured redshifts in our sample.

Figure 3:

a) Histogram of the observed velocities in bins of $1000\ km/s$ for galaxies with $b_J \leq 19.5$. The superimposed dashed curve corresponds to the distribution expected for uniformly distributed galaxies. Note that the Y–axis has been cut at $N = 20$ in order to visualize the distribution outside the Shapley Concentration.

b) Close–up of the distribution of the observed velocities in the range $10000 – 20000\ km/s$; the velocity bin is $500\ km/s$ and the limiting magnitude is $b_J = 19.5$. The solid curve is a Gaussian with $<v> = 14248\ km/s$ and $\sigma = 1083\ km/s$.

Figure 4:

Differential counts as a function of magnitude normalized to those of a reference area near the South Galactic Pole. Solid circles: whole plate 444; open circles: plate 444 without galaxies within 1 Abell radius from the center of the clusters of the Shapley Concentration. The counts of plate 444 have been corrected for galactic absorption. For clearness, error bars (at $1\sigma$) have been drawn only for the solid circles; the errors for the open circles are comparable. Error bars for $b_J > 17.5$ are smaller than the symbol size.

Figure 5:

Wedge diagram of the sample of galaxies in the velocity range $10000 – 24000\ km/s$. The coordinate range is $13^h22^m06^s < \alpha(2000) < 13^h37^m15^s$ and $-32^\circ22'40'' < \delta(2000) < -30^\circ59'30''$. The straight lines drawn in the picture show the projection in right ascension of a circle of 1 Abell radius for each cluster: solid lines refer to $A3562$, dashed and dotted lines to $A3558$ and $A3556$, respectively.

Figure 6:

Isodensity contours of the galaxies in an area of $\sim 2^\circ \times 2^\circ$ around $A3558$. The contours refer to galaxies binned in $1\ arcmin \times 1\ arcmin$ bins; the data have been smoothed with a Gaussian with a FWHM of $6\ arcmin$. The isodensity levels for each magnitude range
have been chosen as integer multiple of the mean number of galaxies per pixel \((< n >)\) in the entire plate. The dots represent galaxies with measured redshifts in the velocity range 11250 – 18000 \(km/s\) and their size is inversely proportional to the radial velocity (the larger the dot the smaller the velocity). The four different sizes for the dots correspond to the velocity ranges 11250 – 13250, 13250 – 14250, 14250 – 15500 and 15500 – 18000 \(km/s\).

a) Galaxies with \(b_J \leq 19.5\); the isodensity levels are \(2 < n >, 3 < n >, 4 < n >, 5 < n >, 6 < n >, \) and \(7 < n >\), where \(< n >= 0.09\). The two dashed straight lines indicate subcondensations \(A\) and \(B\), discussed in the text.

b) Galaxies with \(b_J \leq 18.0\); the isodensity levels are \(2 < n >, 4 < n >, 6 < n >, 8 < n >, 10 < n >, 12 < n > \) and \(14 < n >\), where \(< n >= 0.02\).

c) Galaxies with \(18.0 < b_J \leq 19.0\); the isodensity levels are \(2 < n >, 4 < n >, 6 < n >, \) and \(8 < n >\), where \(< n >= 0.03\).

d) Galaxies with \(19.0 < b_J \leq 19.5\); the isodensity levels are \(2 < n >, 3 < n > \) and \(4 < n >\), where \(< n >= 0.04\).

Figure 7:
Velocity histogram of the galaxies within a) 1 Abell radius around \(A3558\), b) 0.5 Abell radii around \(A3556\) and c) 6 \(arcmin\) around the positions of subcondensations \(A\) (dashed histogram) and \(B\) (solid histogram) in the poor cluster \(SC 1329 -314\). The velocity ranges for galaxies in panel a) and b) have been chosen following the Gaussianity criterion (see text for more details).

Figure 8:
Mean velocity \((C_{B1})\) and velocity dispersion \((S_{B1})\) of \(A3558\) as function of the angular distance from the cluster center. Panels a) and c) refer to the “integral” samples, while panels b) and d) refer to “differential” samples (see Sect.4.1).

PLATE CAPTIONS

Plate 1:
Finding chart for the galaxies with new redshift data in the OPTOPUS field \#2. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond to the identification number of the galaxies as in Table 2.

Plate 2:
Finding chart for the galaxies with new redshift data in the OPTOPUS field \#3. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond to the identification number of the galaxies as in Table 2.

Plate 3:
Finding chart for the galaxies with new redshift data in the OPTOPUS field \#4. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond
to the identification number of the galaxies as in Table 2.
a) first observation; b) second observation.

Plate 4:
Finding chart for the galaxies with new redshift data in the OPTOPUS field #5. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond to the identification number of the galaxies as in Table 2.
a) first observation; b) second observation.

Plate 5:
Finding chart for the galaxies with new redshift data in the OPTOPUS field #6. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond to the identification number of the galaxies as in Table 2.

Plate 6:
Finding chart for the galaxies with new redshift data in the OPTOPUS field #7. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond to the identification number of the galaxies as in Table 2.

Plate 7:
Finding chart for the galaxies with new redshift data in the OPTOPUS field #8. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond to the identification number of the galaxies as in Table 2.

Plate 8:
Finding chart for the galaxies with new redshift data in the OPTOPUS field #9. Reproduced from the ESO Sky Survey R plates; North is at the top, East at the right. Numbers correspond to the identification number of the galaxies as in Table 2.
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