*Nearby Large-Scale Structures and the Zone of Avoidance*
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# The Ophiuchus Cluster and a Large-Scale Structure toward the Galactic Centre

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**Abstract.** The Ophiuchus Cluster is one of the most luminous X-ray clusters in the local Universe, and may be a key cluster for the local large-scale structure. Our preliminary redshift-survey with FLAIR and 6dF for the cluster shows the following: 1) a velocity dispersion of the Ophiuchus cluster is found to be 1050 $\pm$ 50 km s$^{-1}$, which is consistent with its large X-ray luminosity, 2) the cluster accompanies several clusters and groups of galaxies within a distance of 8° from the cluster centre, implying that it is a large and massive enough to be classified as a supercluster, 3) from its closeness to the position of the Great Attractor in the sky, the Ophiuchus Supercluster may play some role in its gravitational potential, as may the Shapley Concentration, and 4) there is an extensive foreground void up to $cz \approx 4000$ km s$^{-1}$ in the survey area, implying that it is a continuation of the Local Void.

## 1. Introduction

The Ophiuchus Cluster is one of the most luminous X-ray clusters in the local Universe (Wakamatsu & Malkan 1981; Watanabe et al. 2001; Ebeling, Mullis, & Tully 2002), and so may be a key cluster in local large-scale structure. However, its basic optical properties, even its velocity dispersion, have not yet been obtained due to its location close to the Galactic Centre ($l = 0.56°, b = +9.27°$). If the Ophiuchus Cluster is large and massive enough to be classified as a supercluster, it may play some role as the Great Attractor because of their closeness on the sky, as the Norma Cluster does (Kraan-Korteweg et al. 1996; Nagayama et al. 2004). We therefore made a redshift survey with FLAIR and the 6dF multi-fibre spectrograph attached to the UK Schmidt telescope at Siding Spring Observatory.

In Section 2, we briefly describe our redshift survey. In Section 3, our results on the structure and dynamics of the Ophiuchus Cluster are given. Large-scale

structures around the Ophiuchus Cluster are analyzed in Section 4, and a brief discussion is given in Section 5.

## 2. Redshift Survey

The Ophiuchus Cluster is highly obscured by $A_V \approx 2.0$ mag due to its closeness to the Galactic Centre. Target galaxies were selected from our galaxy survey, which was made from the SERC J-Sky Survey Atlas with a binocular-type microscope (Wakamatsu et al. 2000; Hasegawa et al. 2000). The galaxy survey was made for 6 SERC fields of 453, 454, 518, 519, 586, and 587, and in total 4158 galaxies with angular sizes larger than 4 arcsec were detected. Less than one-third of them have 2MASS counterparts.

Besides the above-mentioned 6 SERC fields, our redshift survey is extended to a much wider area of $16^h00^m < \alpha < 20^h00^m$, and -35° < $\delta$ < +2.5°. Target galaxies in this area come from the CGCG catalogue. However, additional galaxies had to be found on the SERC J-Sky Survey Atlas, so that all of the fibers of FLAIR or 6dF could be utilized. This always happens for sky close to the Galactic plane. Details of the redshift survey with FLAIR are given by Wakamatsu et al. (2000). From 2002, our survey has been succeeded by the *6dF Galaxy Survey (6dFGS)* at AAO (Wakamatsu et al. 2003; Jones et al. 2004) for the sky above galactic latitude $|b| \geq 10°$, and so is still ongoing. Since then, our redshift survey has concentrated as close to the Galactic plane as possible.

Obscured galaxies near the Galactic plane are about 2 magnitude fainter than those of 6dFGS, and we adopted 2 - 3 times longer exposures than those of 6dFGS. In the core of the Ophiuchus Cluster, many galaxies bright enough to be measured remain unobserved, because their angular separations from other galaxies are too small to place optical fibers properly. Redshift data for approximately 3,000 galaxies will be released in the near future.

## 3. The Ophiuchus Cluster

An $R$-band image of the Ophiuchus Cluster, taken with the UH 88-inch telescope by H. Ebeling, is shown in Figure 1. Around the prominent cD galaxy, more than 20 galaxies are easily identified. Some are very compact, others are of very low surface brightness, and there are few spiral candidates. Many of them are not listed in our galaxy survey catalogue, and so a galaxy survey based on images taken with a large telescope either in optical or $J, H, K$-bands will be quite promising. The number density of galaxies on this $R$-band image are as high as that of the Coma Cluster. The cD galaxy lies at the centre of the cluster core, and so it is adopted as the cluster centre hereafter. Its coordinate is $\alpha = 17^h12^m27.74^s$ and $\delta = -23°22'10.8''$ (J2000.0).

### 3.1. Histograms of Recession Velocities

Figures 2a - 2d show histograms of velocities for galaxies lying within four different radii from the cD galaxy. A big clump around $cz = 9000$ km s$^{-1}$ in Figure 2d corresponds to the Ophiuchus Cluster. In the core within a radius $r \leq 2°$, there appear double peaks around 8500 km s$^{-1}$ and 9700 km s$^{-1}$ (Figure 2a-2b). As the radius increases, however, the dip at 9000 km s$^{-1}$ disappears gradually, and

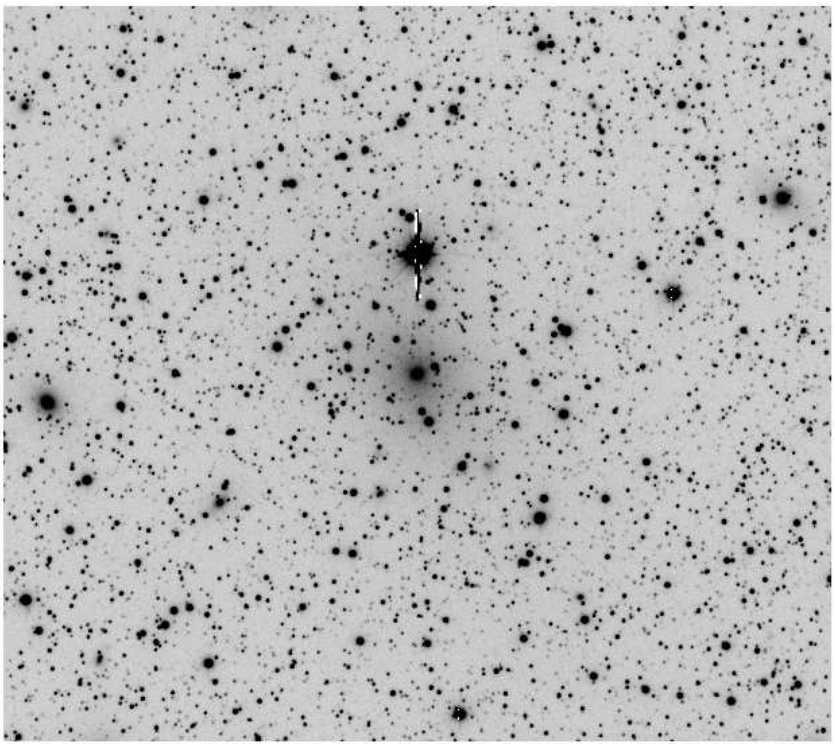

Figure 1. Core region of the Ophiuchus Cluster of galaxies ($4.5' \times 4.0'$) taken with UH 88-inch telescope in $R$-band (courtesy of H. Ebeling). Around the prominent cD galaxy, more than 20 galaxies are easily identified. Some are very compact, others are of very low surface brightness.

the distribution approaches a Gaussian profile centred at 9000 km s$^{-1}$ (Figure 2d). In Figure 2a, the histogram has a sharp lower and upper boundary at 7200 km s$^{-1}$ and 11 200 km s$^{-1}$, respectively. These boundaries do not change as the radius increase up to $r = 5°$, and hence, we adopt a velocity range of 7000 km s$^{-1}$ $< cz <$ 11 200 km s$^{-1}$ for cluster membership.

### 3.2. Distribution of Galaxies in the Sky

Figure 3 shows the galaxy distribution in the sky, plotted with different symbols for four different velocity ranges, i.e., 7000 – 8000 km s$^{-1}$, 8000 – 9000 km s$^{-1}$, 9000 – 10 000 km s$^{-1}$, 10 000 – 11 200 km s$^{-1}$. These intervals were adopted by referring to Figure 2a - 2d. Other galaxies outside of these velocity ranges are not shown, for clarity.

The distribution of galaxies within the two intermediate velocity ranges corresponding to the double peaks in Figure 2a look similar to each other: no spatial segregation can be seen. Galaxies in these velocity ranges distribute fairly uniformly, with a weak concentration to the cluster core. On the other hand, galaxies with velocities deviating more than $\pm$1000 km s$^{-1}$ from the mean recession velocity (9000 km s$^{-1}$; see below) show a strong concentration to the core region ($r \leq 1°$). So, the Ophiuchus Cluster is not a double cluster superposed along the line of sight with a velocity difference of 1200 km s$^{-1}$, but a

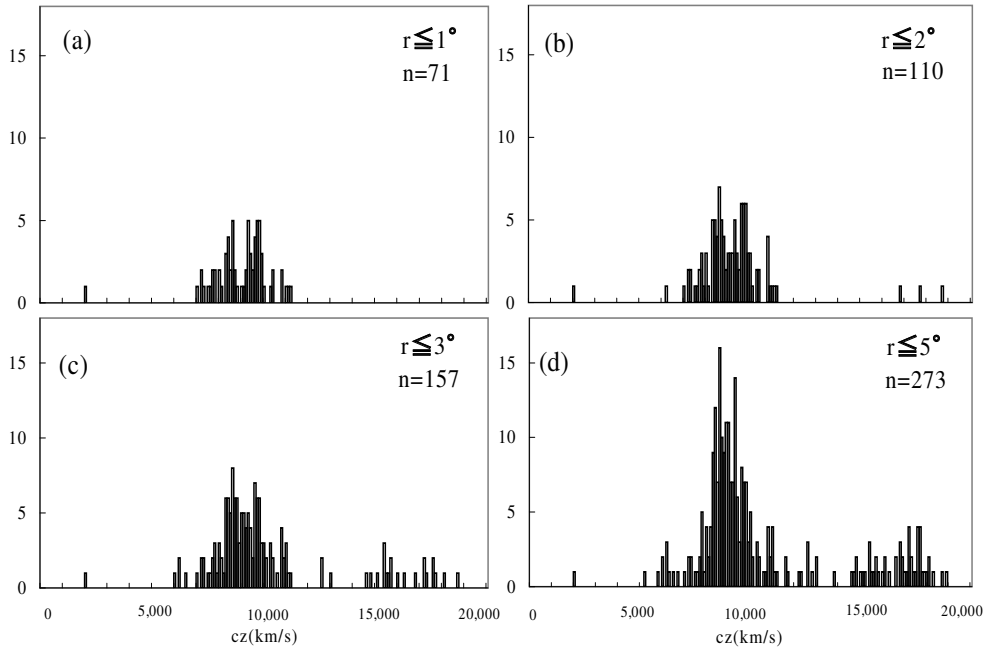


Figure 2. Histograms of recession velocities for Galaxies lying within four different radius $r$ from the cluster centre. Numbers of galaxies indicated at upper right corner of each figure include those of galaxies in $20\,000 < cz < 40\,000$ km s$^{-1}$. The Ophiuchus Cluster corresponds to a prominent clump at $cz \approx 9000$ km s$^{-1}$.

single rich cluster with a large velocity dispersion. A radial profile of the galaxy distribution in the optical survey is given by Hasegawa et al. (2000). This should be revised, when a new galaxy survey in the $J, H$, and $K$-bands, conducted with the Japanese 1.4m infrared survey telescope at Sutherland, in South Africa, is available.

### 3.3. Velocity Dispersion of the Ophiuchus Cluster

Velocity dispersions of the Ophiuchus Cluster, together with mean recession velocities, are calculated based on galaxies lying within various radii from the cD galaxy. The results are given in Table 1. Though mean recession velocities differ slightly for different radii, we adopted $cz = 9045 \pm 30$ km s$^{-1}$, the value evaluated within a radius $r \leq 2°$. This deviates strongly from the recession velocity of the cD galaxy, $8400 \pm 900$ km s$^{-1}$ (Johnston et al. 1981), and close to the near side of the double peaks in Figure 2a. This large deviation should be checked because the recession velocity of the cD galaxy measured by Johnston et al. (1981) is subject to a large uncertainty due to low surface brightness of the core of cD galaxy.

The calculated velocity dispersions attain the maximum value in the innermost radius at $r = 0.5°$, and decrease gradually as the radius increases. This behavior is quite typical for rich clusters of galaxies, and so we adopt $1050 \pm 50$ km s$^{-1}$, the value at the core. This is similar to the velocity dispersion of the Coma Cluster. Such a large velocity dispersion is expected from its X-ray luminosity,

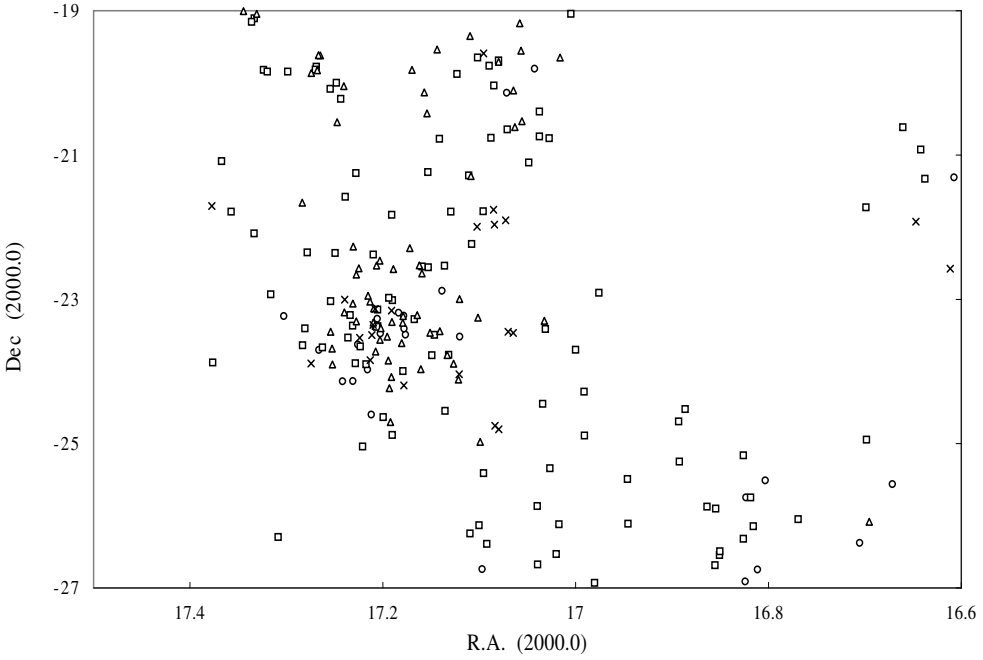


Figure 3. Distribution of galaxies in the Ophiuchus Cluster. Velocity ranges are as follows; circle: $7000 < cz < 8000$ km s$^{-1}$, square: $8000 < cz < 9000$ km s$^{-1}$, triangle: $9000 < cz < 10\,000$ km s$^{-1}$, and cross: $11\,000 < cz < 11\,200$ km s$^{-1}$.

Table 1. Recession Velocity and Velocity Dispersion of the Ophiuchus Cluster

| Radius [degree] | Number of galaxies | Recession Velocity [km s$^{-1}$] | Velocity Dispersion [km s$^{-1}$] |
|---|---|---|---|
| 0.5 | 38 | 9063 | 1046 |
| 1.0 | 69 | 9060 | 967 |
| 2.0 | 104 | 9045 | 933 |
| 3.0 | 127 | 9079 | 932 |
| 5.0 | 197 | 9004 | 827 |

because the Ophiuchus Cluster is one of the most luminous X-ray clusters in the local universe (Watanabe et al. 2001; Ebeling et al. 2002).

## 4. A Large-Scale Structure around the Ophiuchus Cluster

To study large-scale structure around the Ophiuchus Cluster, recession velocity data are surveyed for a wide sky area around the cluster, i.e., $15^h30^m < \alpha < 19^h30^m$, $-45^\circ < \delta < +2.5^\circ$, by referring to databases of the 6dF Galaxy Survey at ROE and NED at NASA. Sloan DSS data in NED were not used, because the survey area in the southern hemisphere is limited to a narrow equatorial region. These data were combined with our own, and cross-checked for duplication and

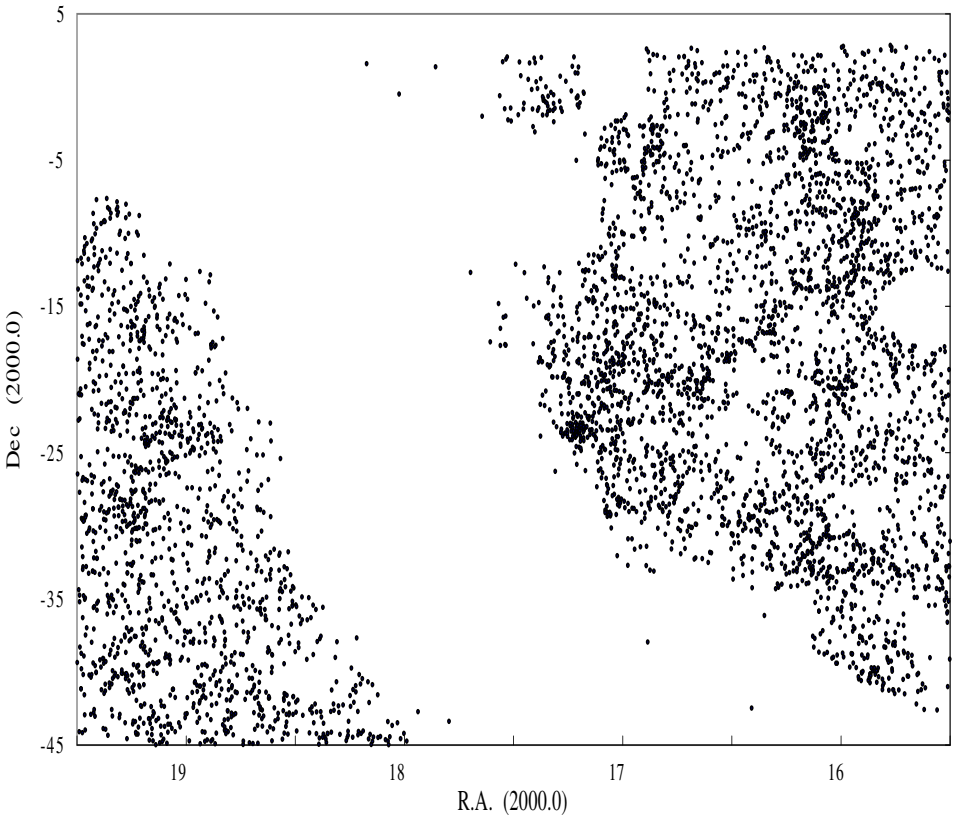


Figure 4. Distribution of 4717 galaxies with measured recession velocities in the wide sky area around the Galactic Centre. Empty areas of a few degree in diameter are areas of no observations and/or patchy dark clouds. The Ophiuchus Cluster is a concentration at $\alpha = 17.2$ h, $\delta = -23.4°$.

consistency of velocities. We compiled, in total, 4717 galaxies with recession velocities in the range 500 km s$^{-1}$ $< cz <$ 40 000 km s$^{-1}$.

The distribution of all these galaxies is show in Figure 4. A wide empty strip running from SW to NE is the Galactic plane, and the Ophiuchus Cluster is easily identified as a clump at $\alpha = 17.20^h, \delta = -23.4°$. Several sky regions for which 6dF Galaxy Survey has not yet been done are easily recognized. Besides these regions, a few empty zones with angular sizes of a few degree can be seen. Many of them correspond to dark clouds, e.g., $\rho$-Ophiuchus clouds at $\alpha = 16.3^h$ and $\delta = -23°$. The present database is neither complete nor uniform in any sense. It is quite difficult to carry out a homogeneous redshift survey around the Galactic Centre, where many dark clouds distribute patchily even up to galactic latitude $b = +30°$ (see the well-known 2MASS All Sky Atlas).

### 4.1. Histograms of Recession Velocities

Nevertheless it is worthwhile, based on these limited data, to examine global properties of the large-scale structure of the local universe around the Galactic Centre region. In Figure 5a - 5d, velocity histograms are shown for galaxies

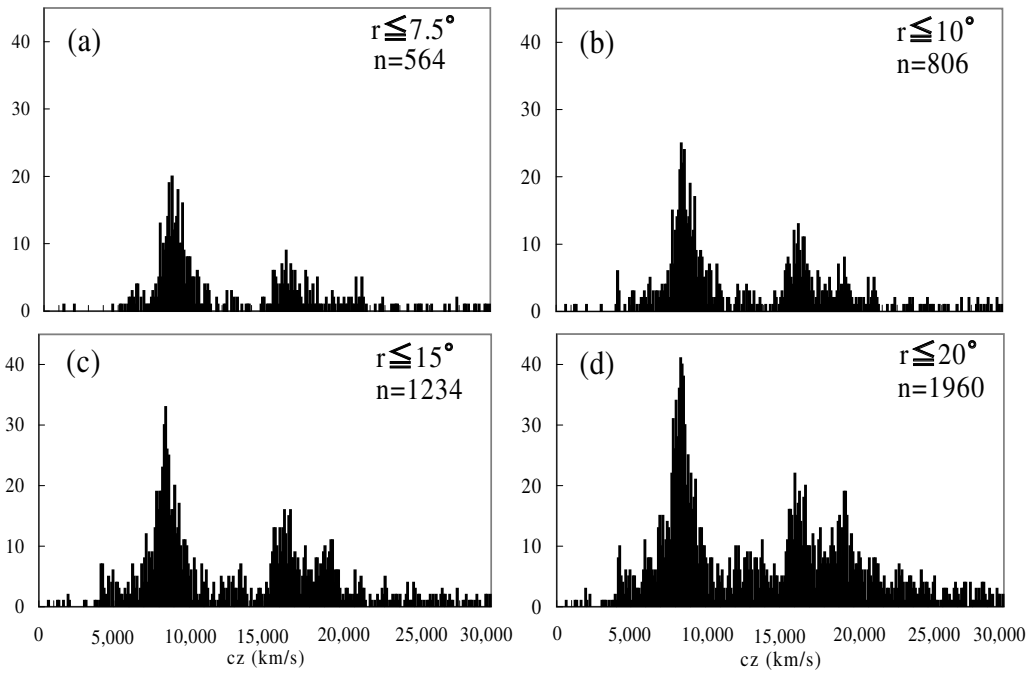


Figure 5. Histograms of recession velocities for Galaxies lying within four different radius $r$ from the cluster centre. Numbers of galaxies are indicated in the upper right corner of each figure. A prominent clump around $cz \approx 9000$ km s$^{-1}$ is the Ophiuchus Supercluster and a related wall.

in the Northern Galactic Hemisphere lying within four different radii from the cluster centre.

From these histograms, the following global features can be seen: (1) A big clump around 9000 km s$^{-1}$ becomes more and more prominent as the radius increases. (2) The next prominent features beyond this are at $cz$ =16 500 km s$^{-1}$, and 19 000 km s$^{-1}$. (3) The number of galaxies with recession velocities less than 4000 km s$^{-1}$ does not increase up to a radius $r = 20°$. This deficiency of galaxies in this velocity range is prominent even for the entire area of the present survey.

### 4.2. Distribution of Galaxies in the Sky

The galaxy distribution in this sky area is shown in Figure 6, where galaxies are plotted with different symbols corresponding to the same four velocity ranges, as in Figure 3, centred at the mean recession velocity of the Ophiuchus Cluster. For clarity, other galaxies outside of these velocity ranges are not plotted. Missing coverage in the sky is due to dark clouds and lack of observations, which can be checked by referring to Figure 4.

A few concentrations can be seen within 10 degrees of the cluster centre. Most of them are clusters of galaxies and groups of galaxies which form a huge clump around $cz \approx 9000$ km s$^{-1}$ in Figure 5a - 5d. They are associated with the Ophiuchus Cluster. So the cluster is found to be large and rich enough to be classified as a supercluster, the Ophiuchus Supercluster. To estimate the total

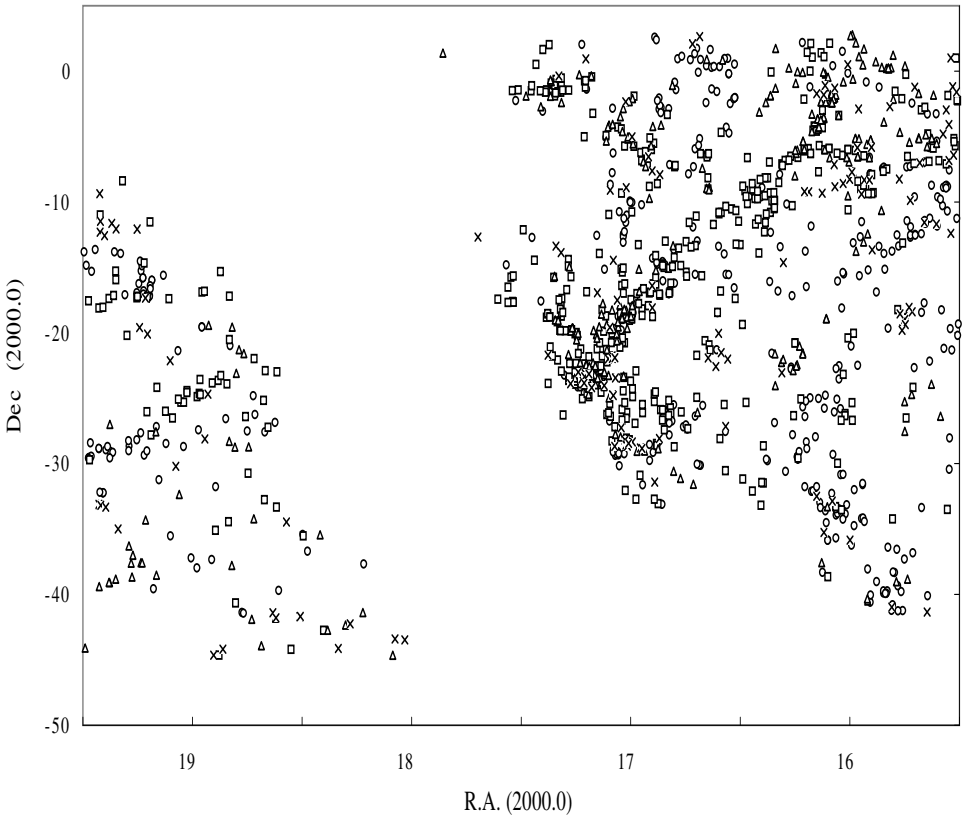


Figure 6. Distribution of galaxies in the wide sky area around the Ophiuchus Cluster. Velocity ranges are as follows; circle: $7,000 < cz < 8000$ km s$^{-1}$, square: $8000 < cz < 9000$ km s$^{-1}$, triangle: $9000 < cz < 10\,000$ km s$^{-1}$, and cross: $11\,000 < cz < 11\,200$ km s$^{-1}$. A prominent wall runs from the Ophiuchus Cluster toward the north-west up to "Point A" at $\alpha = 16.2^h, \delta = 0^\circ$.

mass of this supercluster, it is crucial to uncover hidden structures in its east side with our ongoing galaxy survey in the $J, H$, and $K$-bands.

Another prominent feature is a wall structure starting from the Ophiuchus Cluster, and running to the north-west up to "Point A" at $\alpha = 16.2^h$ and $\delta = 0^\circ$, from where the Hercules Supercluster extends to the north. This is a wall connecting the Ophiuchus and Hercules Superclusters. To demonstrate this structure more clearly, we picked out all the galaxies lying within $\pm$ 5 degree from a line connecting the Ophichus Cluster and "Point A", and plotted their recession velocities as a function of distance from the cluster centre. As shown in Figure 7, a narrow strip at $cz \approx 8500$ km s$^{-1}$ can well be traced up to a distance 30 degree, close to the "Point A". Recession velocity at first gradually decreases down to $cz \approx 8000$ km s$^{-1}$, but from a distance of about 13.5 degrees, it gradually increases up to a velocity of 11 000 km s$^{-1}$, which is the recession velocity of the Hercules Cluster. The total length of this wall is at least 30 degrees on the sky, corresponding to 65 Mpc in linear length ($H_0 = 72$ km s$^{-1}$

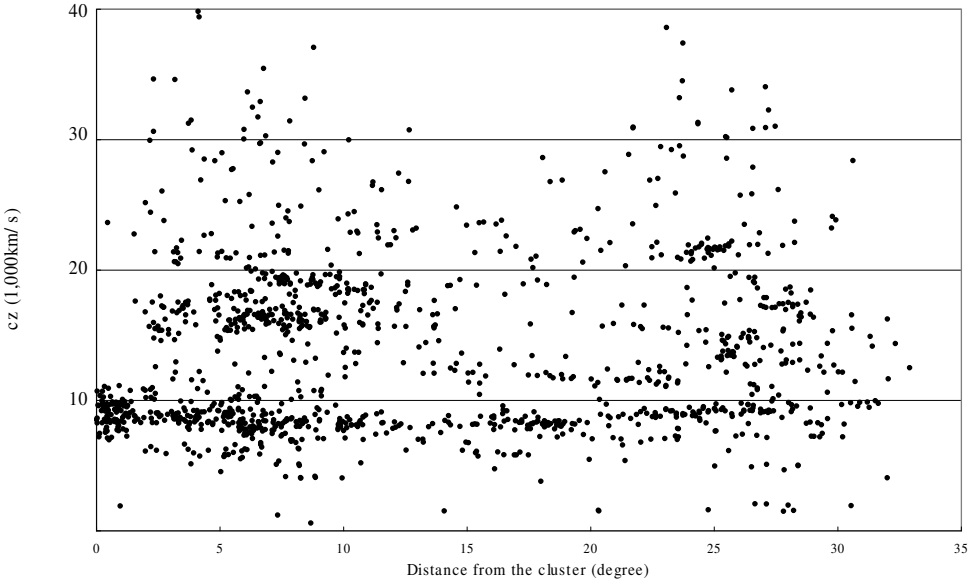


Figure 7. Histogram of recession velocities of galaxies, lying within ± 5 degree from a line connecting the Ophichus Cluster and "Point A", are plotted as a function of distance from the cluster centre. A wall structure can clearly be seen at $cz \approx 9000$ km s$^{-1}$ to a distance 30°.

Mpc$^{-1}$). Note that this wall runs nearly N-S, whereas the Great Wall runs E-W. They cross perpendicularly at the Hercules Supercluster.

### 4.3. Crossing the Galactic Plane

Structures in the Southern Galactic Hemisphere, with a similar velocity range as that of the Ophichus Supercluster, can be examined from Figure 6. Running from NW to SE, centred at $\alpha \approx 19^h00^m, \delta \approx -25°$, a coherent feature of a length of $\sim 12°$ is prominent. Crossing the Galactic plane, this might be a continuation of the Ophiuchus-Hercules Wall.

Though some other concentrations can be seen in Figure 6, galaxies in this velocity range do not form a big clump on a velocity histogram of the Southern Galactic Hemisphere in the present survey area, as does the Ophiuchus Supercluster in the Northern Galactic Hemisphere. The most prominent clumps in the histogram are around $cz \approx 6000$ km s$^{-1}$ and 15 000 km s$^{-1}$.

### 4.4. Local Void

As can be seen from Figure 5a - 5d, the deficiency of galaxies with velocities less than 4000 km s$^{-1}$ is very clear. Less than 10 galaxies are counted in this vast sky region (Figure 5d). This deficiency corresponds to the Local Void identified firstly by Tully & Fisher (1987). Our present analysis implies that the Local Void extends to this sky area in the west, and to this depth of $cz \approx 4000$ km s$^{-1}$, though about 15 galaxies with $cz \approx 1600 \pm 200$ km s$^{-1}$ spread within a radius $\approx 5°$ centred at $\alpha \approx 16^h15^m$, and $\delta \approx -5°$. This vast extension of the Local Void in space and depth is also suggested by HIPASS data (Meyer et al.

2004) in HI survey at Parkes. It is important to delineate its boundary more precisely to understand the dynamics of the local universe.

## 5. Discussion

During this Conference, both Ebeling, Kocevski, Tully et al. and Lucey, Radburn-Smith & Hudson downplayed the role of the Great Attractor. Instead, they claimed that the Shapley Concentration, having recession velocities of about 14000 km $s^{-1}$ and lying at $\approx 40$ degree north of the Norma Cluster (Bardelli et al. 2000), appeared responsible for much of the general streaming in this direction. The Ophiuchus Supercluster lies $\approx 40$ degrees from the Norma Cluster, to the NE direction, and is a much nearer overdensity than the Shapley Concentration. In this respect, the Ophiuchus Cluster may contribute as much as the Shapley Concentration, to the general acceleration. A more extensive redshift survey in this sky region is urgently needed to disclose the entire structure around the Ophiuchus Cluster and also the Local Void.

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