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Light upon the Structures of the Universe

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Our knowledge of the observed large scale structures in the nearby universe is reviewed. The relationship between the local gravity field, the total extragalactic light flux past the Local Group, and its velocity through the Cosmic Microwave Background is established. Ω is deduced. If the contrasts in density of the galaxy distribution are three times those of all matter (as found in biased galaxy formation models), the universe is closed.

1. INTRODUCTION

Raman studied light all his life but never fulfilled his ambition to study astronomy. I hope this small contribution in his honour would have interested him.

In the early 1920s V. M. Slipher showed that most extragalactic nebulae were moving away from us[1]. Hubble's great struggle to determine extra-galactic distances led him to the law[2] governing this expansion $v = H$. To use this law not only must the distance r be known but the correct zero point from which the radial velocities should be measured must be determined. This is done by rewriting the law $v_H + v_\odot \cdot \hat{r} = Hr$ where v_H is the heliocentric radial velocity and, choosing $v_\odot$ to give best fit. Following pioneering work on the Sun's velocity by Hubble and others, the IAU agreed to de Vaucouleurs' standard prescription that the redshifts of extragalactic nebulae should be corrected for a motion of the Sun of 300 km/s in the direction $l = 90$, $b = 0$. Although later determinations give some small transverse components too, de Vaucouleurs' prescription is within 50 km/s of the best zero point today.

Thus, when radiometers were used by Conklin and Bracewell[3,4] to find the motion of the Sun through the Cosmic Microwave Background (CMB), astronomers expected a motion of around 300 km/s towards a direction within 20° of $l = 90$, $b = 0$. They were wrong! The radio observations consistently gave velocities of around the present value (see review by Lubin & Villela[5]) 360 km/s but toward $l = 267$, $b = 50$, about 130° away from the direction predicted. This implies that the locally determined zero point found by deVaucouleurs' prescription is in reality moving at 600 km/s towards $l = 268$, $b = 27$. Not only is this motion (hereafter referred to as the Local Group's motion) non-zero, it is even greater than the raw motion of the Sun relative to the CMB. The correction to the local zero-point made things worse. Why?

What is found is not just a motion of the Local Group but a motion of all nearby galaxies over and above the general Hubble expansion since it is these that are used to find the optical zero-point. Current theory attributes motions of galaxies to gravitational perturbations due to density fluctuations in the universe which grow themselves by Jeans's gravitational instability. Although 600 km/s is quite large for a large-scale velocity perturbation, nevertheless it can be accommodated within current theories. There are three ways to test the hypothesis that the velocity has been caused by gravity:

(i) To look for the density enhancements that cause the gravity.
(ii) To map the flow field of galaxies, determine the deviations from Hubble flow more generally and to relate them to the density distribution, using the galaxies as tracers.

(iii) To determine the gravity field on the Local Group and so check whether it is parallel to the velocity generated and of sufficient magnitude.

Here we shall consider (i) and (ii) rather briefly and concentrate on (iii) where work with O. Lahav has made the most recent progress.

2. DENSITY ENHANCEMENTS

To get a picture of the density field the best we can do is to map the density of luminous matter. The dark matter may be differently distributed but it cannot be observed at present. The theory of biased galaxy formation suggests that galaxies form more readily per unit mass in regions of higher density, so that the density of luminous matter will give a somewhat exaggerated picture of the total density variations. To parametrize this idea in the simplest possible way we shall take

$$\frac{\Delta\rho}{\rho_0} = \frac{1}{b}\,\frac{\Delta\rho_L}{\langle\rho_L\rangle}, \tag{2.1}$$

where ρ_0 and $\langle\rho_L\rangle$ are the current mean total density of the universe and the mean density of luminous matter, respectively. b is the bias parameter which is one if galaxies trace the total matter in an unbiased fashion. Unfortunately distances to galaxies are not generally available so the best one can hope for is a large number of galaxies with redshifts. In spite of sterling work by Huchra, Fairall[6], Da Costa and others, complete redshift data is only available for a somewhat biased sample of rather bright galaxies, so in much of the sky the observed galaxy density is strongly affected by observational selection. To get around such problems I show here not the density of galaxies but their distribution over the sky. In figures 1 and 2 the galaxies which give the greatest light on Earth are given the largest and brightest symbols. The figures are equal area projections of the distribution of galaxies with major diameters ≥ 1 arcmin in the Northern and Southern hemispheres. The Northern data are from Nilson's UGC; the southern from the ESO-Uppsala catalogue supplemented in the $-2.5° > \delta > -17{\cdot}5°$ strip by the Morphological Catalogue which is less complete. In the Northern sky the most prominent feature is the Virgo Cluster ($v_r \simeq 1000$ km/s) through which passes the strong supergalactic band of bright galaxies. After crossing the dark zone where the Milky Way's dust has obscured the extragalactic world, this band crosses the curved arrow shaped feature at whose head is the Perseus cluster and whose shaft is the Pisces Chain. Both have redshifts of around 5000 km/s. In the Southern hemisphere the most prominent feature is the Pavo-Indus-Telescopium band which is again obscured by the Milky Way before extending to the broad concentration of galaxies in Centaurus. This extends South and West to the nearer Centaurus Cluster which is seen as a bright knot just north of the Milky Way. North of the Galactic Plane, but further West lies the Hydra cluster which is joined to the Centaurus cluster by the region of enhanced density called the Hydra-Centaurus Super-cluster. Fairall gives evidence that both are linked with the more northerly Centaurus concentration and to the Pavo-Indus-Telescopium chain.

3. STREAMING MOTIONS

The Local Group's motion lies towards Hydra, and both Shaya[7] and Tammann & Sandage[8] suggest that the Hydra-Centaurus supercluster with some help from Virgo gives the gravity that caused the Local Group's motion. This was contested by the Samurai (Burstein *et al.*[9], Dressler *et al.*, Lynden Bell *et al.*[10], Lynden-Bell[11]) in their studies of galaxy streaming who found the Centaurus clusters to have a rapid excess motion. They therefore suggested that these were victims, not culprits, and the real cause of the motion might lie in the Great Attractor which they identified with the concentration of galaxies in Northern Centaurus at ~4500 km/s redshift. Currently there are conflicting data on the excess outward motions of the Centaurus clusters[12,13,14], so these arguments must be considered uncertain until the new observations are fully reduced. The main finding of the Samurai that a large scale streaming of galaxies exists out to at least 3200 km/s with a value of around 600 km/s, but on average more towards Centaurus than Hydra, still stands. Much of this motion arises in the Southern sky and it is not parallel to the Local Group's motion but about

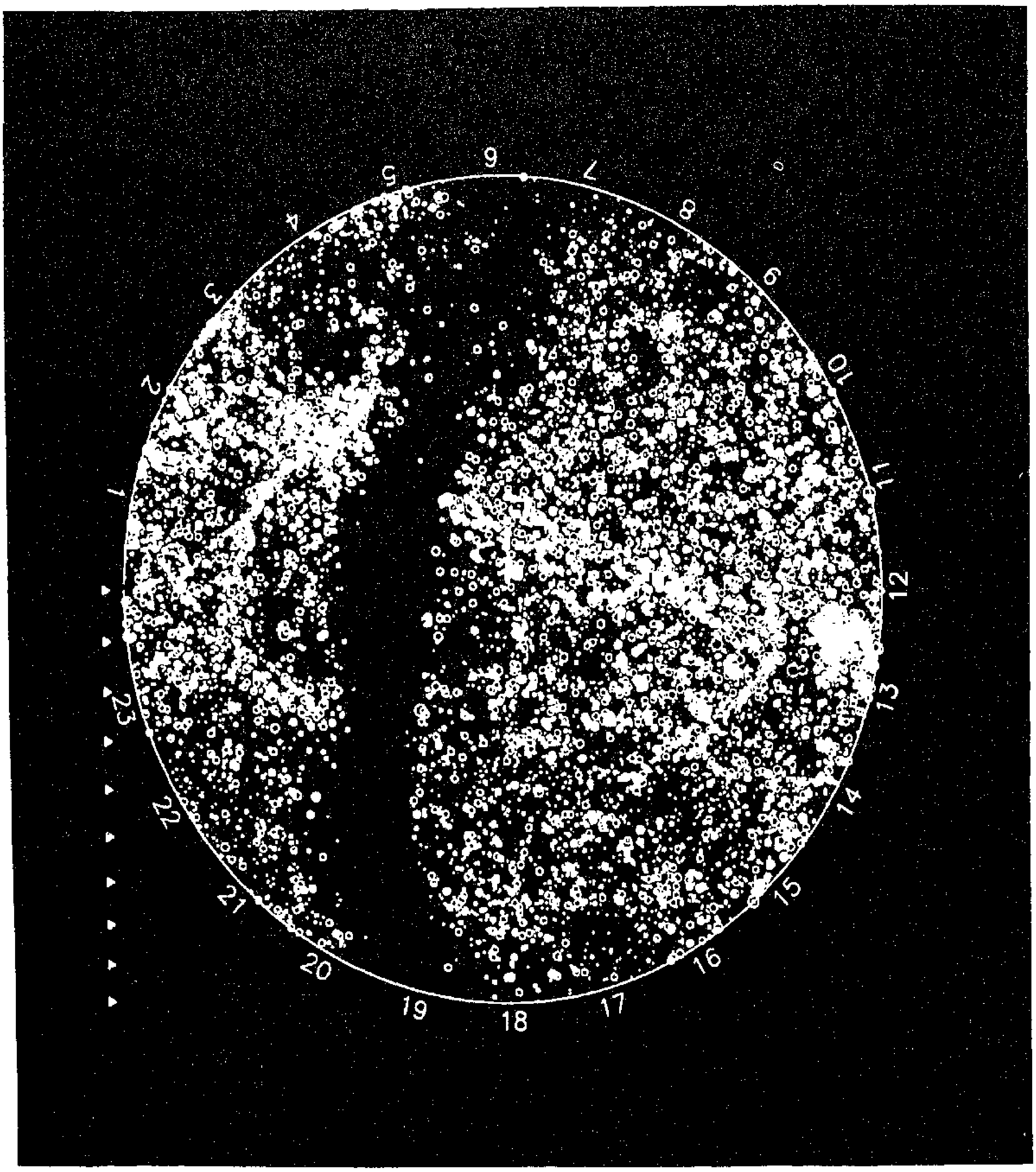

Figure 1. Equal area projection of northern hemisphere galaxies in Nilson's Uppsala General Catalogue centred on the pole.

35° further around in Galactic Longitude. There is no reason why these motions should be parallel – one gives some average velocity of galaxies over quite a large region and the other gives a local mean velocity of very nearby galaxies.

4. LOCAL GRAVITY

The light from a galaxy falls off as r^{-2}. The gravity field from a galaxy falls off as r^{-2}. Thus light fluxes and gravity fields remain proportional however far from the galaxy we may be. Furthermore, another galaxy of twice the luminosity is not unlikely to have roughly twice the total mass. Thus for statistical purposes we may probably assume there is some overall average mass-to-light ratio and that the gravity field from every galaxy is some multiple of the light flux received from it. Adding all such contributions vectorially, we see that the net gravity field on the Local Group should be proportional to the net directed flux of extragalactic light. Since the gravity field is thought to be

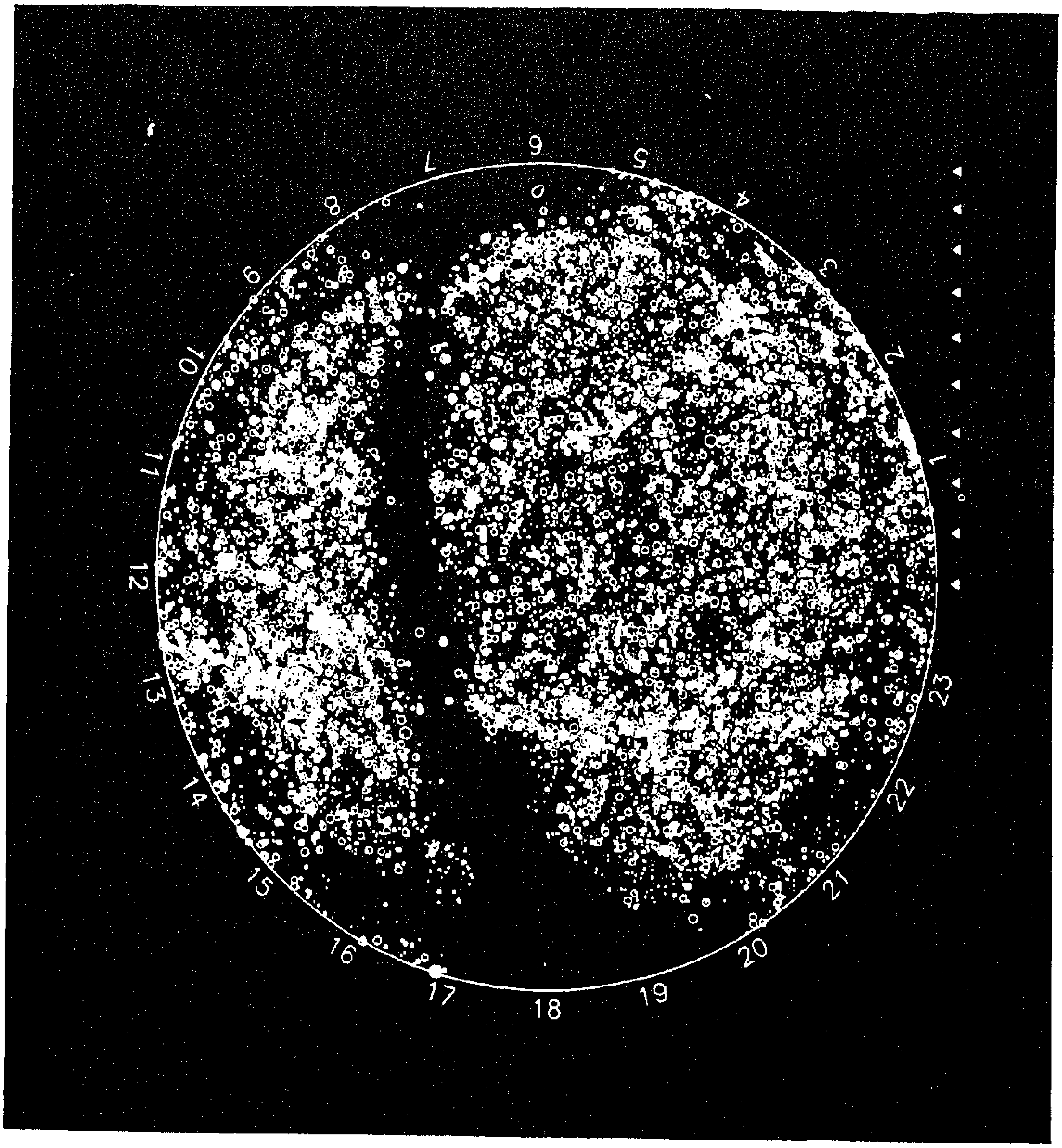

Figure 2. Equal area projections of southern hemisphere galaxies (with diameters > 1′) in the ESO/Uppsala Catalogue centred on the pole. North of $\delta = -17{\cdot}5°$ the galaxies come from the MCG except that north of $\delta = -2{\cdot}5°$ they come from UGC.

responsible for the Local Group's velocity, it follows that this velocity should be aligned with the direction from which the net extragalactic light flux comes.

Are these vectors parallel?

To find out we must evaluate the light flux. The available galaxy catalogues do not allow a direct evaluation but they do give major angular diameters, θ, for the galaxies. Since θ^2 falls like r^{-2} and since luminosities are roughly proportional to θ^2 we use $\Sigma\theta^2\hat{\mathbf{r}}$ in place of the net light flux. I exclude details of our compensation for different catalogues, galactic absorption and incomplete data, *etc.* Those interested can find a detailed description in Lynden-Bell, Lahav & Burstein, 1989[15].

4.1 *The Net Directed Extragalactic Light Flux*

The surface brightness σ of the extragalactic sky after exclusion of Local Group galaxies may be expanded in spherical harmonics in the form

$$\sigma(l,b) = M + \mathbf{P}\cdot\hat{\mathbf{r}} + \hat{\mathbf{r}}\cdot\mathbf{Q}\cdot\hat{\mathbf{r}} + \dots . \qquad (4.1)$$

where $\hat{\mathbf{r}} = (\cos l \cos b, \sin l \cos b, \sin b)$. **P** is the dipole moment of the extragalactic brightness, **Q** is the (traceless) quadrupole moment *etc.* $4\pi M$ is the total extragalactic light falling on earth. The total directed extragalactic light flux is

$$2\pi \int_{-1}^{+1} \mathbf{P}\mu^2 d\mu = \frac{4\pi}{3}\mathbf{P},$$

where μ is cos the angle measured from the direction of **P**. In accord with the procedures of the last section, we replace luminosity by θ^2. The evaluation of the corresponding **P** is made by summing

$$\mathbf{P} = \frac{3}{4\pi} \sum_{\text{galaxies}} \theta^2 \hat{\mathbf{r}} \tag{4.2}$$

we may also define $\mathbf{P}(>\theta)$ by summing over only galaxies with corrected diameters $>\theta$ and $P(<\mathrm{v})$ by summing only over galaxies with actual or estimated redshifts less than v. Similarly we find the corresponding monopoles

$$M(>\theta) = \frac{1}{4\pi} \sum_{\substack{\text{galaxies} \\ >\theta}} \theta^2 . \tag{4.3}$$

Our studies of $P\ (>\theta)^{16,17}$ and of $P\ (<v)^{15}$ show that most contributions to P arise at velocities < 4000 km/s and from galaxies with diameters $> 2'$. However, for comparison with the observed velocity we need the total dipole, not just that from galaxies with diameters $> 1'$. From our diameter function for galaxies, it is clear that more than 1/3 of all the light from aggregates of galaxies at 10,000 km/s will come from galaxies $> 1'$ in diameter. We would like to correct the contributions of all the observed galaxies to allow for galaxies that form part of the same luminosity function as those observed, but which are smaller than $1'$. Beyond 10,000 km/s we have too few galaxies to allow us to perform such a correction with accuracy, but since most of the dipole arises from $v < 4000$ km/s, the omission of galaxies beyond 10,000 where the catalogues are becoming seriously incomplete, is not of great concern. Averaged over such large scales, it appears that the universe is too uniform to give a significant extra contribution to the dipole. From our diameter function for galaxies we find the function $L(>D)$, which gives that fraction of the total light (or rather, the total D^2) which arises from those galaxies with diameters $>D$. The function $L(D)$ is well fitted by (see figure 3)

$$L(D) = (1 + t/2)/(1 + t/5)^4 ,$$

where

$$t = (D/D_L)^2$$

and

$$D_L = 6538 \text{ arcmin.km/s}$$

(i.e. a galaxy with $D = D_L$ would subtend 1 arc minute if it were placed at a distance corresponding to 6538 km/s in the Hubble flow). A galaxy with recession velocity v will have diameter $D = v\theta$. With a diameter limit of θ_m, the associated galaxies with $D \leq v \cdot \theta_m$ will have been omitted. Thus we will have recorded only a fraction $L(\theta_m)$ of the total light.

To compensate for their omission we must weigh each observed galaxy with a factor $1/L(v\theta_m)$. We have only $\sim$ 1/3 of the redshifts of our galaxies so when v is unknown, we replace $1/L(v\theta_m)$ by its average taken over all those galaxies with the same angular diameter and with known redshifts. Thus our formula for the total P is

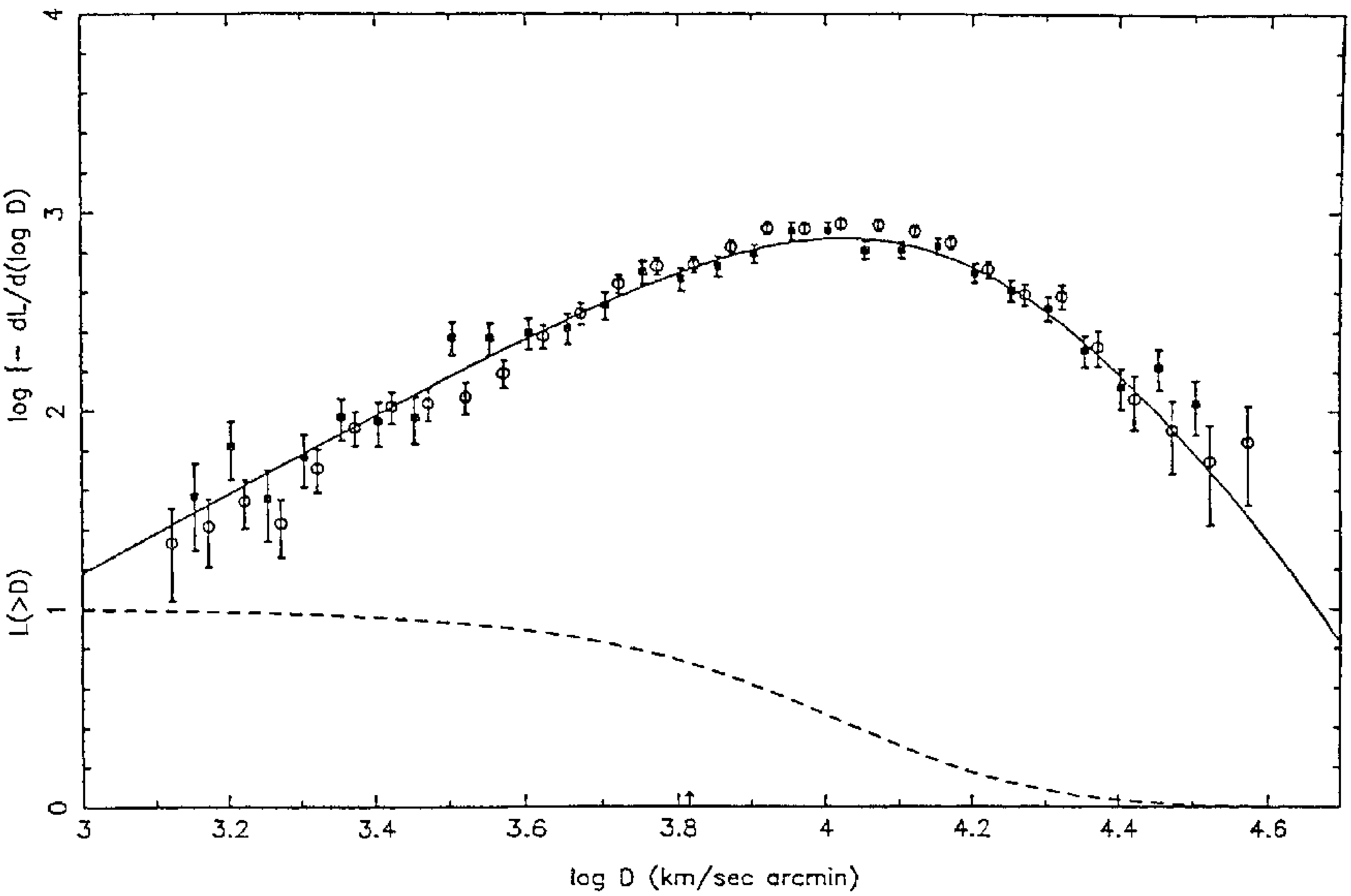

Figure 3. Below the function $L(D)$ giving the fractions of the total 'light' from all galaxies that arises from those of diameter greater than D. For light we have substituted D^2 as explained in the text. Above the differential distribution of $L(D)$, i.e. $-\,\mathrm{d}[\log L(D)]/\mathrm{d}\log D$.

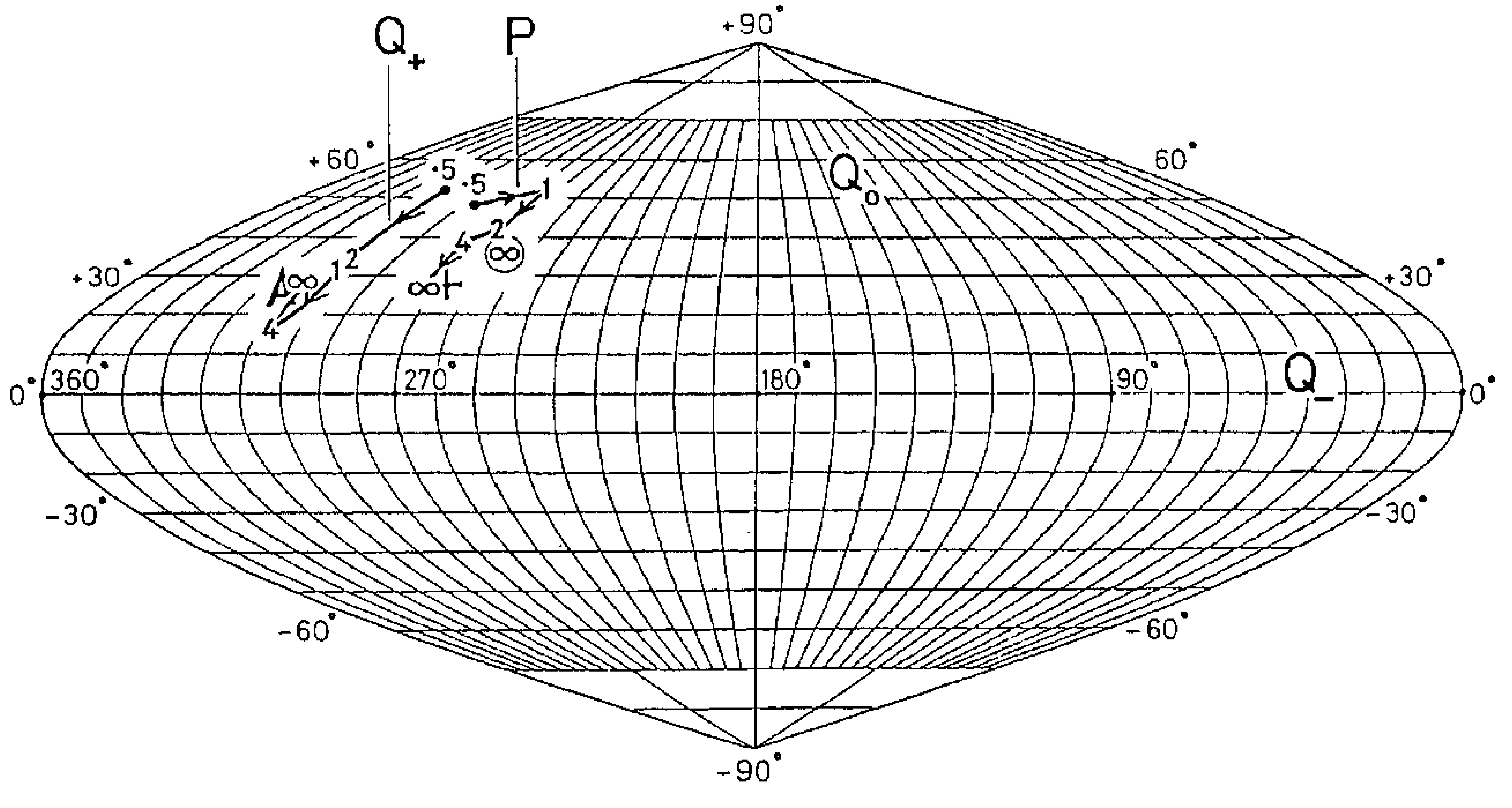

Figure 4. The directions of the net optical dipole **P** arising from galaxies at < 500, < 1000, < 2000 and < 4000 km/s together with an estimate '∞' of the total dipole. ∞ is the equivalent direction in which a 'mean sky' estimate of the obscured regions has replaced the 'mock sky' estimate that interpolates from neighbouring areas. Also shown are the principal axes of the light quadrupole **Q**. Q^- is close to the supergalactic pole, Q^+ points at the Great Attractor A. Q_0 is generally small but it is larger than Q^+ at $v < 1000$ where its direction (illustrated) lies towards the Ursa Major cloud of nearby galaxies.

$$\mathbf{P} = \frac{3}{4\pi} \sum_{\substack{\text{galaxies} \\ >1'}} \theta^2 \, \hat{\mathbf{r}}/L \, , \tag{4.4}$$

where $1/L$ is replaced by $\langle 1/L \rangle$ (a function of θ) when the velocity of the galaxy is unknown. The directions of the vectors $\mathbf{P}$ $(<v)$ as v is varied from 500 km/s to >10,000 km/s are shown in figure 4. Evidently there is remarkable agreement between the direction of the total $\mathbf{P}_\infty$ and the motion of the Local Group through the Cosmic Microwave Background. This is a significant improvement on the first uses of the IRAS data for this purpose (Yahil, Walker & Rowan-Robinson[18], Meiksin & Davis[19]) but the Meurs & Harmon IRAS sample gives similar agreement (Harmon, Lahav & Meurs[20]). It is interesting that the principal positive axis of the brightness quadrupole points straight at the Great Attractor.

5. THE COSMOLOGICAL DENSITY Ω

Peebles[21] shows that small perturbations in the density of the universe generate peculiar velocities $\mathbf{v}$ and gravity fields $\mathbf{g}$ related by

$$\mathbf{v} = (2/3)\Omega^{-0.4}\mathbf{g}/H, \tag{5.1}$$

where Ω is the density parameter of the universe and H is Hubble's constant. For discussion of non-linear corrections to this formula see Lynden-Bell[11]. For small θ, where the universe is almost uniform, $\theta^2 \, \mathrm{d}M/\mathrm{d}\theta$ is given by

$$\theta^2 \mathrm{d}M/\mathrm{d}\theta = (\langle \rho_L \rangle/4\pi) \int_0^\infty -\mathrm{d}L/\mathrm{d}D_0 \, D_0 \, \mathrm{d}D_0 = \langle \rho_L \rangle \, \bar{D}_0/4\pi \tag{5.2}$$

D_0 is the true diameter of a galaxy which is related to the velocity × angular diameter, D, by $HD_0 = D$.

Now from the definitions of $\mathbf{P}$ and b

$$\mathbf{P} = \frac{3}{4\pi} \int \hat{\mathbf{r}} \Delta\rho_L \, (4\pi r^2)^{-1} \mathrm{d}^3 r$$

$$= (3b/4\pi) \int \hat{\mathbf{r}} \, \frac{\Delta\rho}{\rho_0} \, (4\pi r^2)^{-1} \mathrm{d}^3 r \; \langle \rho_L \rangle \; = \; (3b/16\pi^2)(\langle \rho_L \rangle/\rho_0)\mathbf{g}. \tag{5.3}$$

Using 5.1 and 5.2 this may be re-written

$$\frac{\mathbf{P}}{\theta^2(\mathrm{d}M \,/\, \mathrm{d}\theta)} = 3\Omega^{-0.6}(b/\bar{D})/\mathbf{v}, \tag{5.4}$$

where

$$8\pi G \, \rho_0 \,/\, 3 = \Omega H^2 \text{ and } \bar{D} = H \, \bar{D}_0.$$

Since H is poorly known but the velocities of galaxies are known, we know $L(D)$ not $L(D_0)$ so $H \, \bar{D}_0 = \bar{D}$ is far more accurately known than $\bar{D}_0$. From our catalogues data we evaluate $\mathbf{P}$, $M(>\theta)$ and $\bar{D}$ is evaluated from our determination of $L(D)$. We give two evaluations of $\Omega^{0.6}/b$ using different compensations for missing regions of the sky called Mock Sky and Average Sky. Since the main problems occur in the Milky Way, we also evaluate $\Omega^{0\cdot6}/b$ from the z components of equation (5.4) which are hardly affected by the missing regions behind the Milky Way.

	Mock Sky	*Average Sky*
$\Omega^{0\cdot6}/b$	0·312	0·490
ditto based on P_z	0·320	0·374

We can determine Ω only if we know b. The unbiased assumption ($b = 1$) yields $\Omega = 0{\cdot}17$ for $\Omega^{0\cdot6}/b = 0{\cdot}347$, but for that same data the very acceptable $b = 2{\cdot}9$ yields $\Omega \simeq 1$. Thus, provided galaxies give a three times greater density contrast than the mean of all matter, the universe will be closed and finite.

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