THE DISTRIBUTION OF GALAXIES IN RELATION TO THEIR FORMATION AND EVOLUTION

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Abstract. The distribution of galaxies on the sky is not random, but has structure on a scale of ~ 30 Mpc. Similar structure in the cosmic background radiation is not present. Another expected source of structure in the background radiation is the finite size of the light horizon in the early Universe. The lack of observable structure in the background radiation implies extreme initial isotropy. Quantum effects may be responsible for this isotropy, and for the initial perturbations from which galaxies and clusters of galaxies formed.

The isotropic 2.7K cosmic background radiation (Penzias and Wilson, 1965) and the recession of the extragalactic nebulae (Hubble, 1929) are strong evidence that the Universe expanded from a hot, dense fireball. The expansion rate $H_0 = 50$ km s^{-1} Mpc^{-1} (Abell, 1972) implies, in the context of the isotropic solutions of the Einstein equations (with no cosmological constant), that the expansion began $t_0 \lesssim 20 \times 10^9$ yr ago.

The early Universe was hot, and the matter and radiation were in equilibrium. Fluctuations in density involving less than the critical Jeans' mass could not grow, and dissipated. As the Universe expanded and cooled, this critical mass increased as $t^{3/2}$ to reach a limiting value of $M_J \sim 10^{18}\, \mathfrak{M}_\odot$ shortly before the Universe had cooled enough for the matter to recombine. As the matter recombined, the critical mass dropped to $M_J \sim 10^6\, \mathfrak{M}_\odot$. Fluctuations involving more than $\sim 10^6\, \mathfrak{M}_\odot$, that survived the period of dissipation before recombination, were then gravitationally unstable and grew as $\delta\varrho/\varrho \sim t^{2/3}$ (for $\delta\varrho/\varrho < 1$). Calculations of the transfer function for fluctuations through the period of dissipation (Peebles and Yu, 1970; Weinberg, 1971) show that fluctuations involving more than $\sim 10^{11}\, \mathfrak{M}_\odot$ could survive. These fluctuations in the density of the early Universe are seen today in the irregularities of the matter distribution.

The nearby galaxies are shown on an equal-area projection in Figure 1. They are plotted from the catalogue of Shapley and Ames (1932) which lists the galaxies with $m_{pg} \leqslant 13$. For comparison, a random space distribution viewed through a plane-parallel layer of absorbing material (with half-thickness $a = 0.5$ mag) aligned along the galactic plane has been simulated in Figure 2 using the same number of points as in Figure 1. The great circle of the galactic plane is traced out by the zone containing no galaxies in both Figures 1 and 2. The distribution of the random galaxies is more homogeneous than that of the real galaxies. The real galaxies are concentrated along the supergalactic equator, a band, nearly perpendicular to the galactic plane, running from the left of the top to the lower right of the centre in Figure 1. The prominent concentration to the upper right of centre in Figure 1 contains the Virgo cluster. The local supercluster (de Vaucouleurs, 1955) consists of the galaxies concentrated along

John R. Shakeshaft (ed.), The Formation and Dynamics of Galaxies, 75–84.

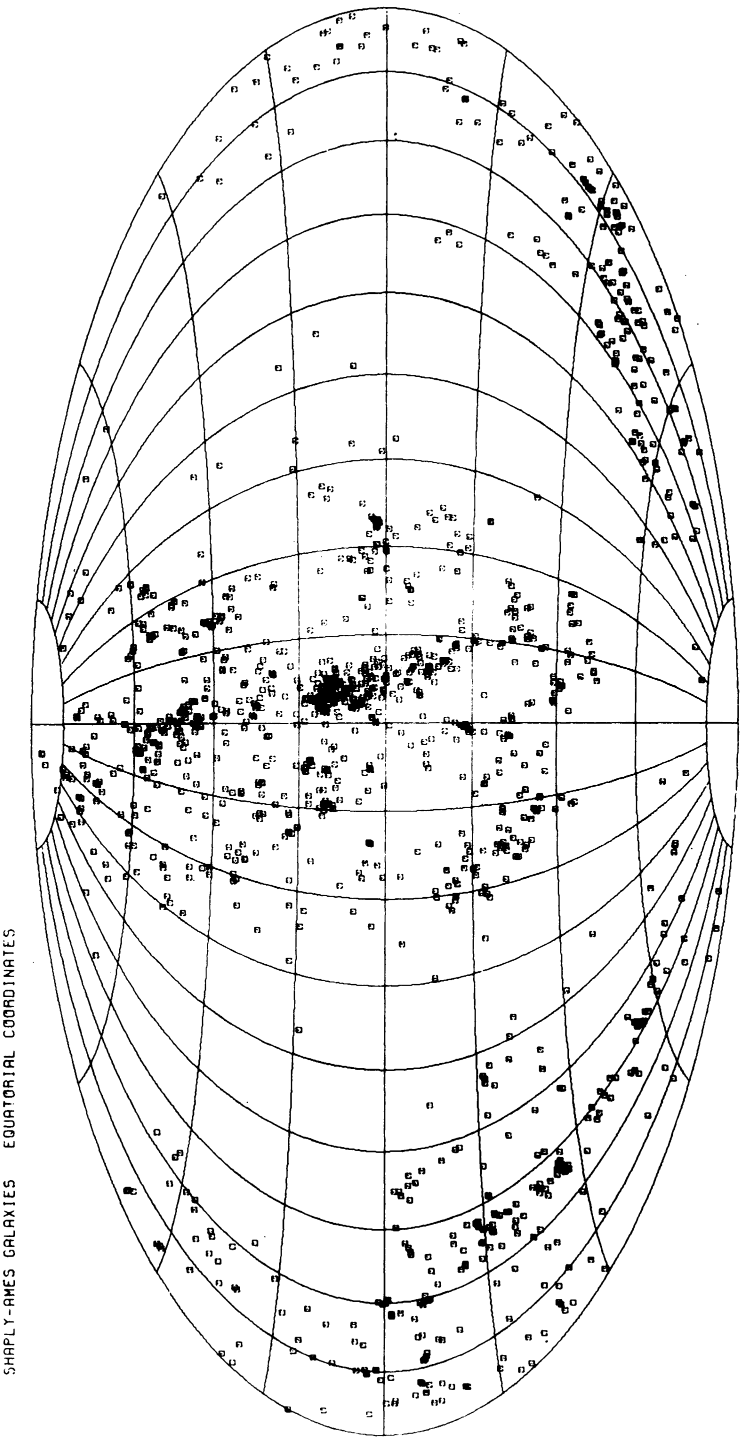

Fig. 1. Galaxies from the catalogue of Shapley and Ames plotted on an equal-area projection.

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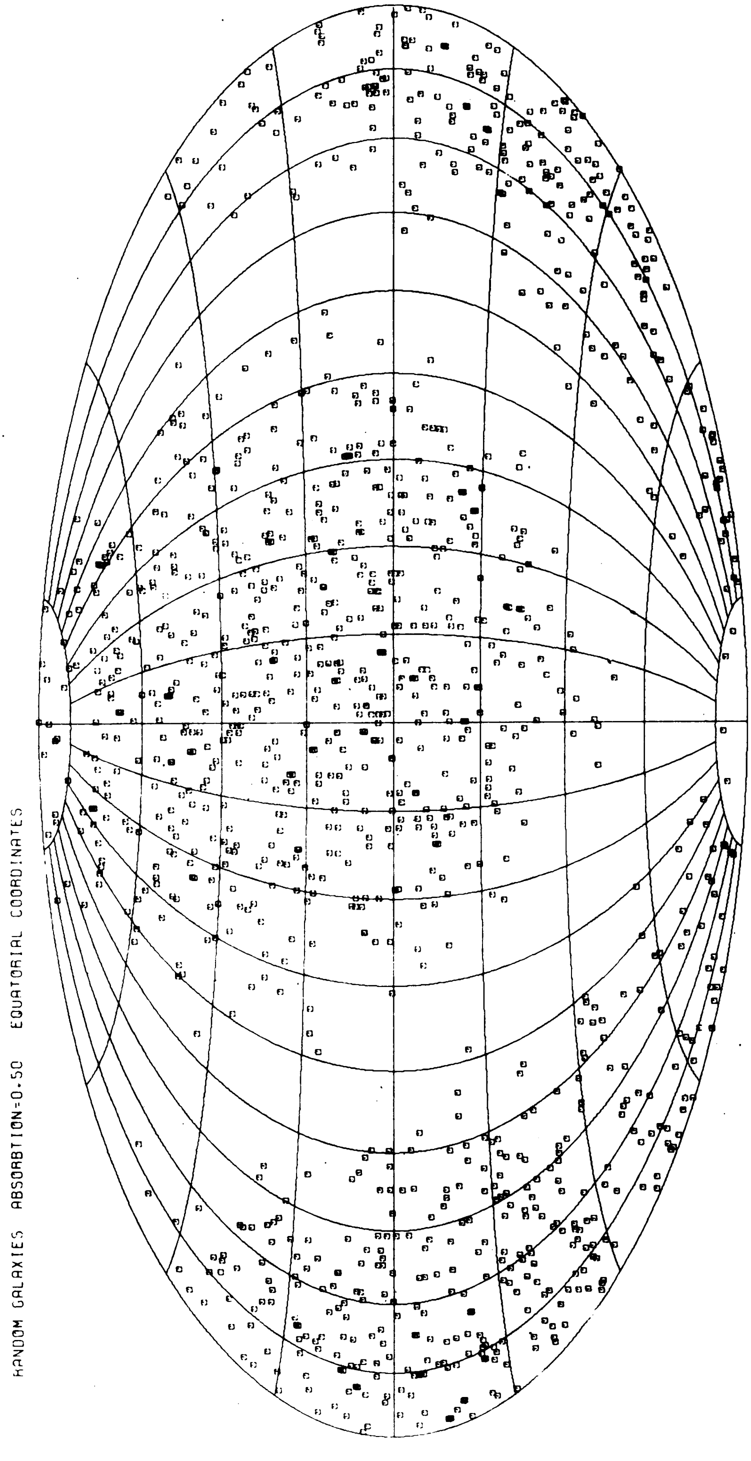

Fig. 2. Simulated, random, space distribution of galaxies seen through a plane parallel layer of absorbing material of half-thickness $a = 0.5$ mag. This figure contains the same number of points as Figure 1.

the supergalactic equator, including the Virgo cluster. It has a scale of ~ 30 Mpc and contains $\sim 10^{14}\,\mathfrak{M}_{\odot}$.

In Figures 3–6 are the galaxies in the catalogues of Zwicky and his co-workers (Zwicky *et al.*, 1961–68). Figure 3 reaches to $m_{pg} \leqslant 13$, the same as Figure 1. More distant galaxies dominate the successively fainter magnitude intervals shown in Figures 4–6. The galaxy distribution in Figure 6 has a mottled appearance on a scale of $\sim 20°$ on the sky. This corresponds to ~ 30 Mpc at the distance of the galaxies in Figure 6. Structure in the matter distribution on a similar scale has been found out to greater distances in the Abell clusters (Hauser and Peebles, 1973) and in the galaxy counts of Shane and Wirtanen (Peebles and Hauser, 1974).

The fluctuations in the early Universe which produce structure in the matter distribution at the present day would also produce anisotropy in the temperature of the cosmic background radiation. If we assume that the density of the intergalactic medium is low, then the background radiation comes to us from $z \sim 1500$ when it was last scattered during the recombination era. The angular scale of the temperature fluctuations expected from galaxies and superclusters is

$$\theta \sim 2q_0^{2/3}(MGH_0/c^3)^{1/3} \sim 1'.$$

The amplitude of the expected fluctuations is $\Delta T/T \sim \frac{1}{3}(\delta\varrho_0/\varrho_0)/(1+z) \sim 10^{-3}$. In a comparison of their recent observations with the detailed calculations of the expected fluctuations from forming clusters of galaxies (Peebles and Yu, 1970), Carpenter *et al.* (1973) found that the upper limit to the observed fluctuations is less than the fluctuations that are expected by about a factor of two. However, if the intergalactic medium is hot and dense, then the optical depth produced by Thomson scattering may be large by $z \sim 10$ (Gunn and Peterson, 1965) and the fluctuations in the temperature of the cosmic background radiation would be considerably reduced.

Another effect which should contribute to structure in the distribution of matter, and to fluctuations in the temperature of the cosmic background radiation, is the finite size of the light horizon when matter and radiation decoupled. Only fluctuations on a scale smaller than that of the light horizon can be smoothed out, since communication is only possible with the portion of the Universe contained within the light horizon. Also, the smoothing process can only be effective while the radiation can be scattered by the matter. The proper distance to the light horizon is $r_H \sim c/H_0 \times (2/q_0)^{1/2}(1+z)^{-3/2}$, corresponding to ~ 150 kpc ($q_0 = 1$, $H_0 = 50$ km s^{-1} Mpc^{-1}) at $z \sim 1500$ when recombination took place. Material then on our light horizon is now at $r_H(1+z) \sim 200$ Mpc. If the smoothing process was effective over only $\leqslant 15\%$ of the distance to the light horizon at recombination, then we would expect to find structure on a scale of $\geqslant 30$ Mpc in the matter distribution. Structure appears to be present in the distribution of galaxies on a scale of ~ 30 Mpc.

However, the corresponding structure is not present at a similar amplitude in the 2.7 K cosmic background radiation. If the optical depth of the intergalactic medium is small, then the cosmic background radiation has not been scattered since the matter recombined, and background radiation from areas of the sky separated by

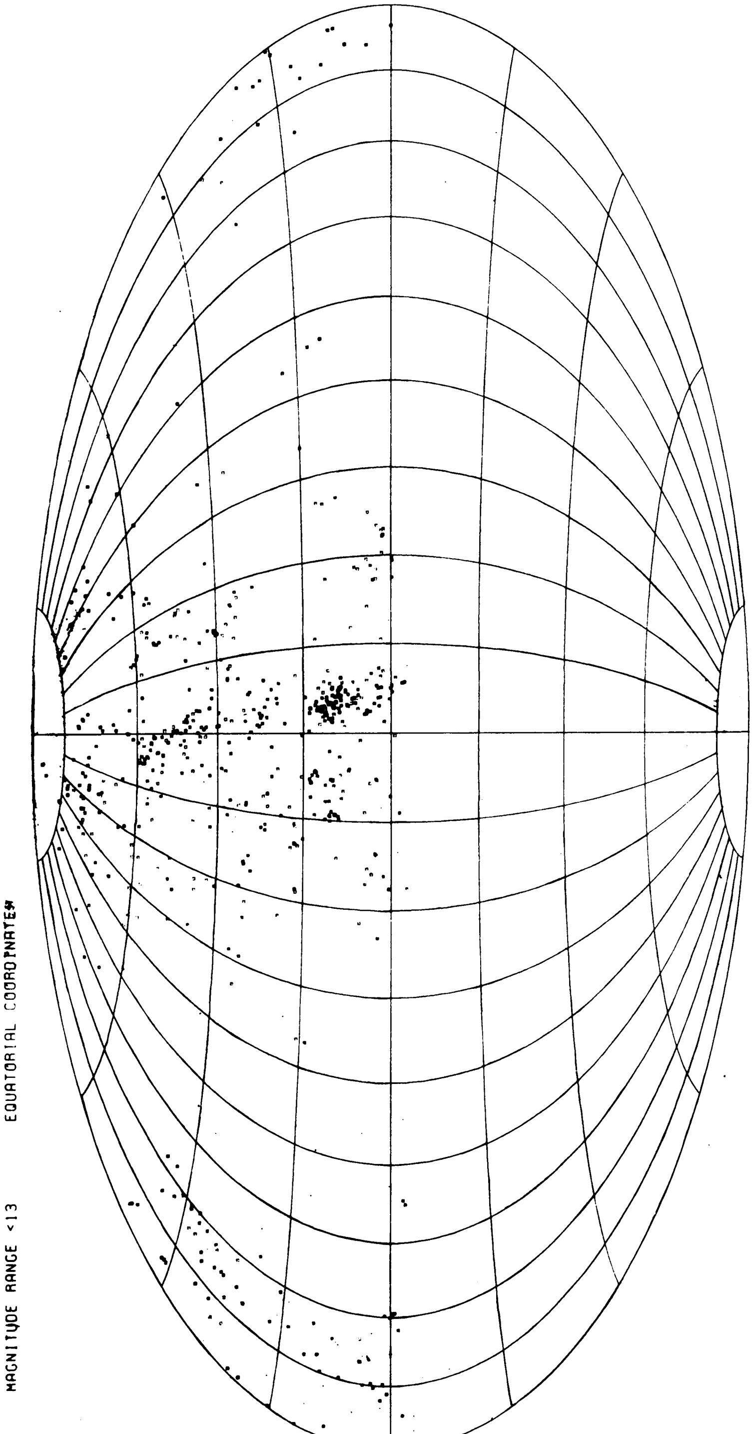

Fig. 3. Galaxies with $m_{pg} < 13$ from the catalogues of Zwicky *et al.*

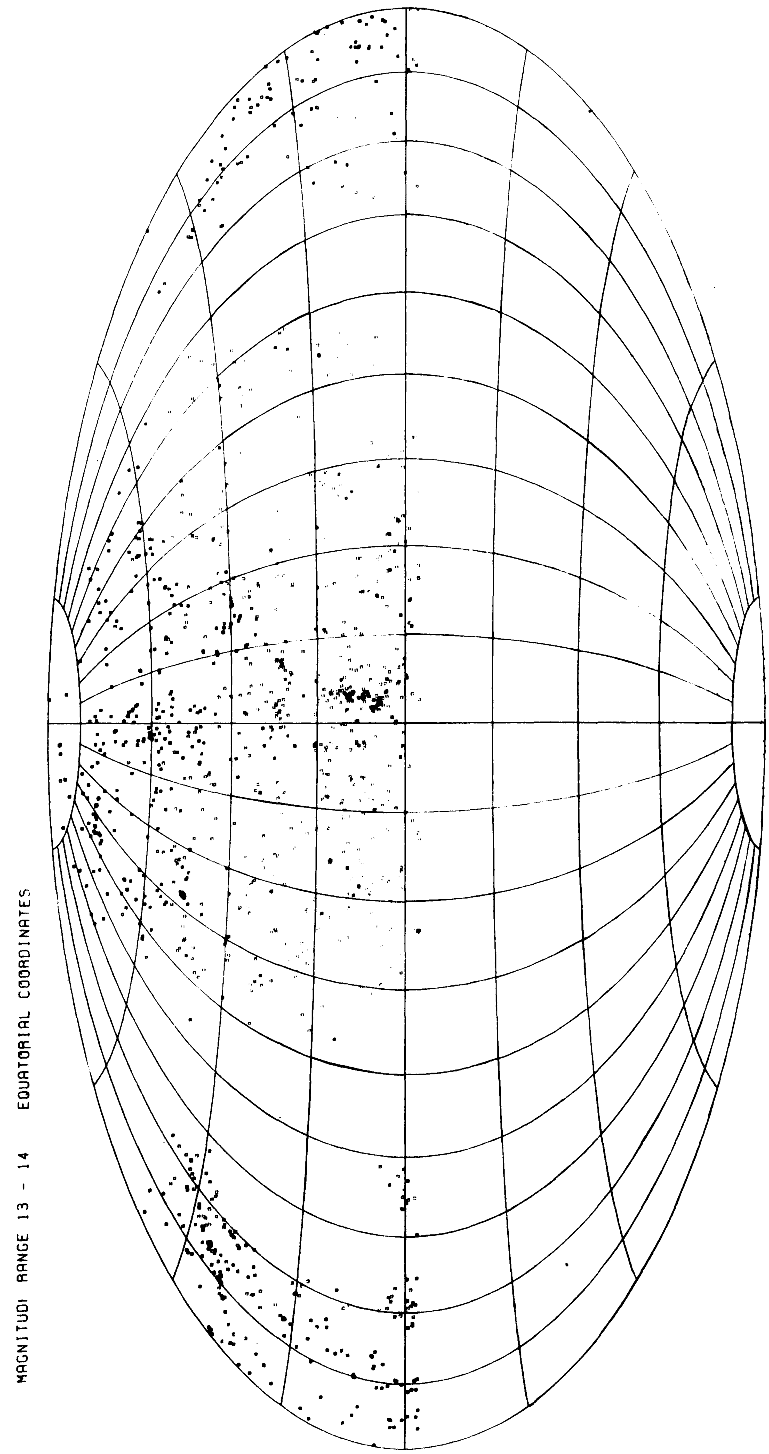

Fig. 4. Galaxies with $13 \leq m_{\rm pg} < 14$ from the catalogues of Zwicky *et al.*

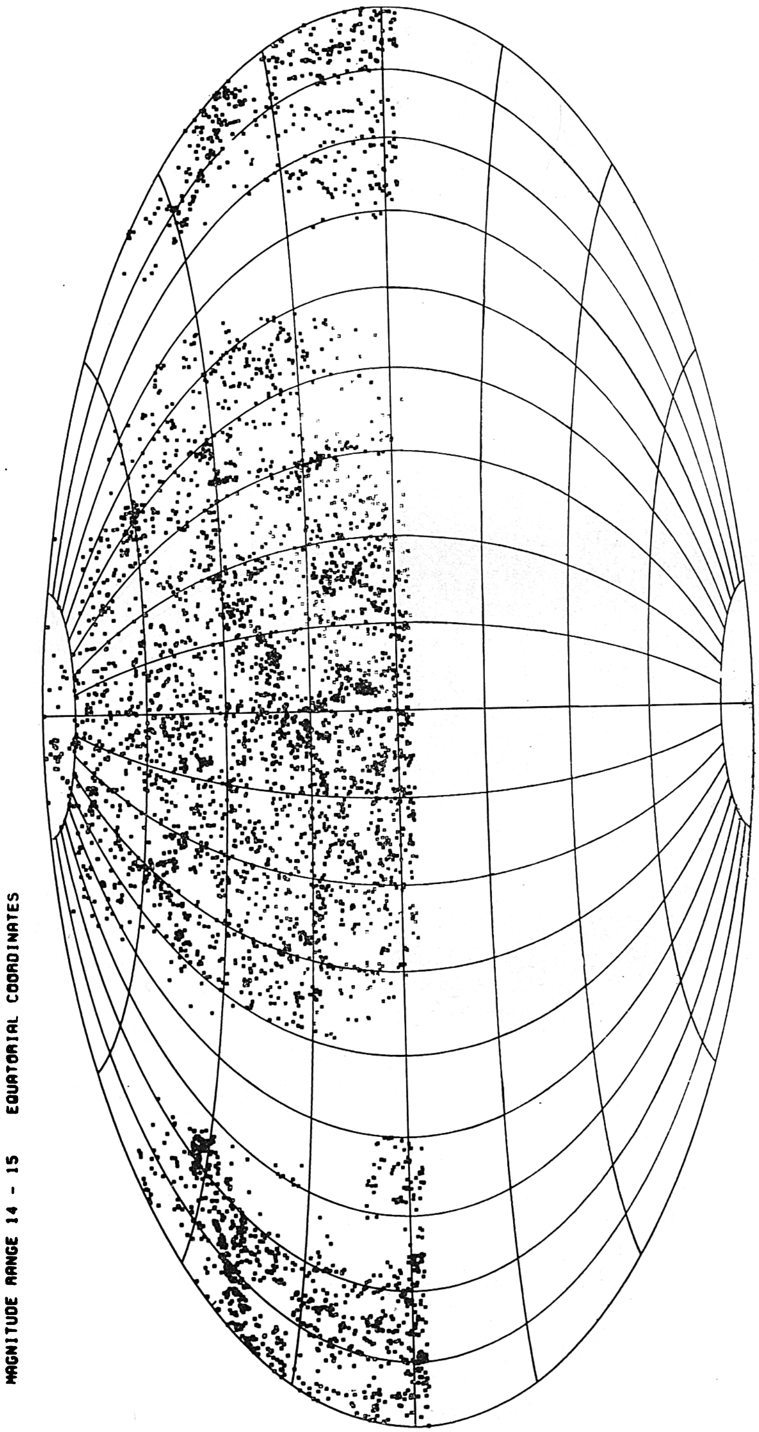

Fig. 5. Galaxies with $14 \leq m_{\mathrm{pg}} < 15$ from the catalogues of Zwicky *et al.*

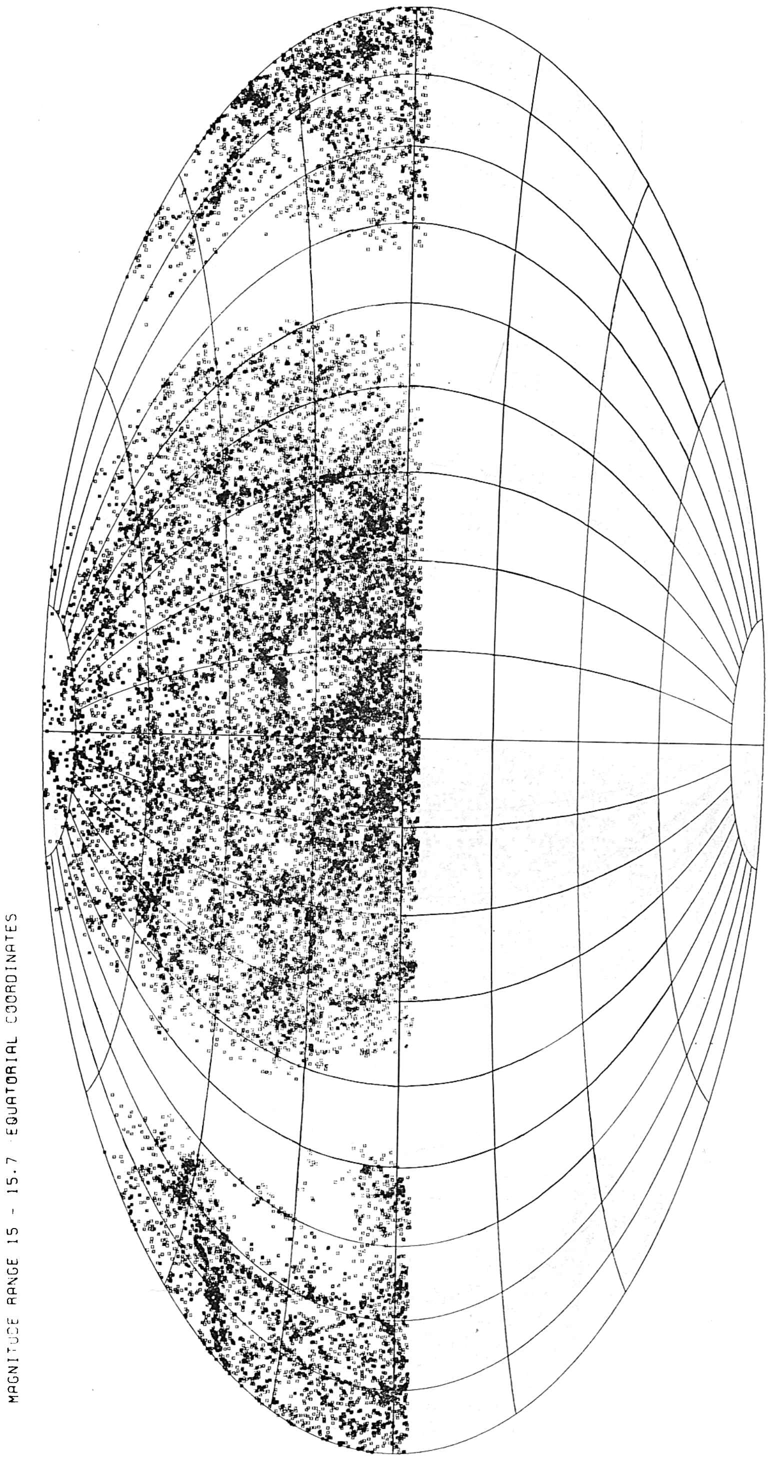

Fig. 6. Galaxies with $15 \leqslant m_{\mathrm{pg}} \leqslant 15.7$ from the catalogues of Zwicky *et al.*

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more than $\theta \sim \sin^{-1}(2\,q_0/z)^{1/2} \sim 2°$ comes from regions of the Universe separated by more than the light horizon at the time of recombination. Alternatively, if the intergalactic medium is optically thick by $z \sim 10$, the half-angle subtended by the light horizon when the radiation was last scattered is then $\theta \sim 25°$. Yet no temperature fluctuations greater than $\Delta T/T \sim 10^{-3}$ are observed, implying that the Universe is isotropic to better than 0.1%.

In the framework of general relativity, it is hard to avoid the conclusion that such an overall uniformity of the Universe was a special initial condition. Initial inhomogeneities tend to grow. Thus isotropy at a latter time implies isotropy at the beginning. Collins and Hawking (1973) found that the set of spatially homogeneous universes that approaches isotropy at infinite times is of measure zero in the space of all spatially homogeneous universes. As a way of justifying the special initial condition required to produce such a Universe, they argued that this may be the only type of Universe in which galaxies and intelligent life may form, and thus the Universe in which we live must be of this type.

I suggest that initial isotropy may come about through the action of quantum effects which force the early Universe into a structure of maximal symmetry. When the age of the Universe is less than $t \sim 10^{-44}$ s, the Compton wavelength of the mass contained within the light horizon is greater than the light horizon, and continuous fluid models based upon general relativity are inappropriate (Harrison, 1967). When the age of the Universe reaches $t \sim 10^{-23}$ s, the light horizon has expanded to the Compton wavelength of the π-meson and the massive hadron resonances that make up the early Universe may then begin to decay. Carlitz *et al.* (1973) found that large density fluctuations are produced during the hadron era, and that these are not completely damped out during the period of dissipation that occurs before recombination. In this picture, the present observable structures in the matter distribution, the superclusters and galaxies, are produced by the decay products of massive hadron resonances. The 2.7 K cosmic background radiation originates in the secondary gas of photons, leptons and baryons which builds up from the products of hadron decay.

Thus a forced initial isotropy would allow us to understand how regions of the Universe that were out of communication come to have the same temperature, and the large fluctuations produced by massive hadron resonances in the early Universe would provide the required perturbations for the formation of galaxies and clusters of galaxies.

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DISCUSSION

E. M. Burbidge: In the plot of 15–15.7 mag galaxies, there was a hole in the distribution which seemed to correspond to the high density region in the brighter galaxies in the Virgo cluster. Did it actually coincide?

Peterson: The region of low density lies 10° to the NE of the concentration of bright galaxies.

Tifft: There may be more incompleteness in the Zwicky catalogue at faint limits in *rich* regions, due to observer selection when counting.

Peebles: The Zwicky catalogue was only advertised to be complete to magnitude 15.5.

G. de Vaucouleurs: We have compared various recent catalogues of galaxies and are very puzzled that we see no trace of the supergalactic concentration of galaxies in the Zwicky catalogue although his absolute counts, the number of galaxies per square degree to his stated limit ($m = 15.5$), are in excess of the density extrapolated from counts to fainter limits, i.e. he finds a local excess, as would be expected if his counts are still affected by the Local Supercluster. But when we study the galaxy density vs. supergalactic latitude to compute the supergalactic concentration, it vanishes at the limit of the Zwicky catalogue. However, about ten years ago one of Dr Abell's students, Mr Carpenter, counted galaxies to a fainter limit ($m \simeq 16$) and still revealed a supergalactic concentration, (*Publ. Astron. Soc. Pacific.* **73**, 324, 1961) so there seems to be a discrepancy in the data.

Irving: Can these 'patches' be due to patchy galactic absorption?

Peterson: Peebles has correlated the Shane-Wirtanen catalogue ($m < 19$) with the Zwicky catalogue ($m < 15.5$) and finds that these low density regions are not due to galactic absorption since they change in size as the magnitude limit of the catalogue changes.

Abell: Zwicky himself (Herzog, E., Wild, P., and Zwicky, F.: 1957, *Publ. Astron. Soc. Pacific* **69**, 409) was very much aware that his galaxy counts indicate a shortage of faint galaxies in areas where there is a greater-than-average numerical density of brighter galaxies. He attributed this to intergalactic absorption by dust in the region of the brighter, nearer galaxies. Of course, this circumstance, as Dr Tifft suggests, may be a selection effect. At least, Zwicky was aware of the phenomenon and called attention to it.