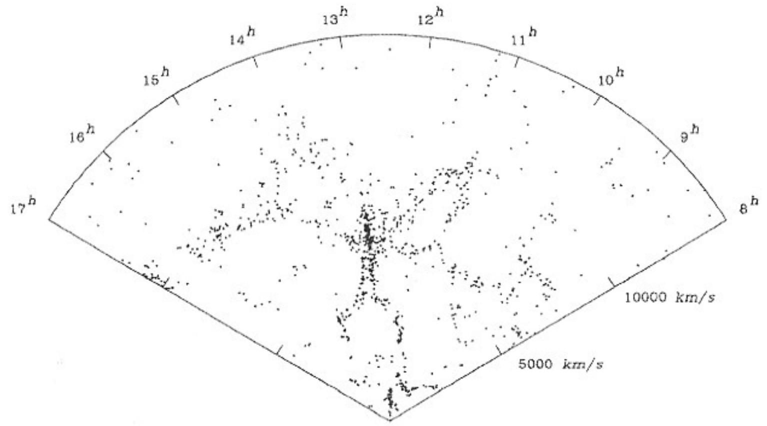

FIGURE 22.7 A slice of the universe: each dark dot represents a galaxy.

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho_0}\right)^{1/2} \approx H_0^{-1}. \tag{22.23}$$

Thus, the average density of a supercluster must be

$$\rho_0 \approx \frac{3\pi H_0^2}{32G} \approx 2\times 10^{-26}\,{\rm kg\,m^{-3}} \approx 3\times 10^{11} M_\odot\,{\rm Mpc^{-3}}. \tag{22.24}$$

This is equivalent to 14 hydrogen atoms per cubic meter; even compared to the low-density coronal gas of the interstellar medium, the average density of a supercluster is not great.

The arrangement of clusters and groups into superclusters was first discovered by the astronomer Gerard de Vaucouleurs, who pointed out that the Local Group and the Virgo Cluster, along with other nearby groups and clusters, were arranged in a flattened "supercluster." This is now known as the Local Supercluster, or the Virgo Supercluster. More distant superclusters are most easily seen in three-dimensional maps of the universe, rather than in two-dimensional projections on the sky (such as Figure 22.1). A "redshift map" of the universe can be made by using the redshift z of a galaxy as a surrogate for its distance, since $d \propto z$ for small z. To make such a redshift map, you can start by measuring redshifts for galaxies in a long, narrow strip of the sky.

Among the earliest redshift maps of this kind were those produced in the 1980s by the CfA Redshift Survey.[6] A wedge of the universe from the CfA survey is shown in Figure 22.7. To make this redshift map, redshifts were measured for galaxies with right ascension $8^h < \alpha < 17^h$ and declination $26.5^\circ < \delta < 32.5^\circ$, down to a limiting apparent magnitude $B = 15.5$ mag. For the 1061 galaxies meeting these criteria, $v_r = cz$ was

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[6] CfA stands for the Harvard–Smithsonian Center for Astrophysics.

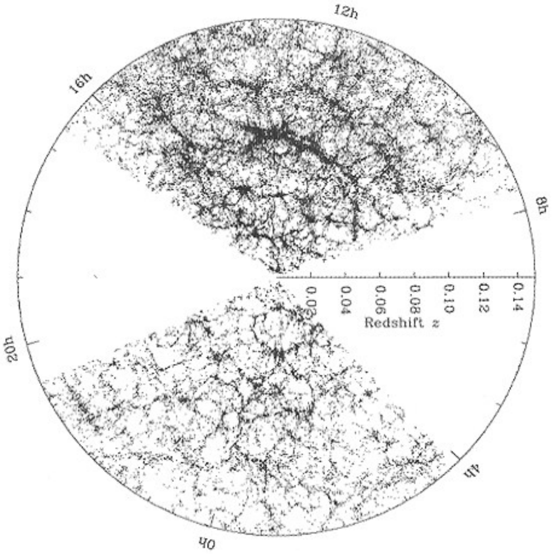

FIGURE 22.8 A bigger slice of the universe: each tiny dark dot represents a galaxy.

plotted versus right ascension. Note that dense regions in the redshift map tend to be elongated, while the underdense regions, or voids, are more nearly spherical (or more nearly circular, in the case of this thin slice).

A more recent redshift map, with a fainter apparent magnitude limit, is shown in Figure 22.8. This shows a slice from the Sloan Digital Sky Survey (SDSS). When the SDSS is complete, it will have provided redshifts for about a million galaxies in the Northern Galactic Hemisphere, down to a limiting apparent magnitude $m_r \approx$ 17.8 mag.[7] This gives a detailed map of the galaxy distribution out to a redshift $z \sim 0.2$, corresponding to a distance $d \sim (c/H_0)z \sim 900$ Mpc. Thus, the Sloan Digital Sky Survey probes the universe to four times the distance of the CfA Redshift Survey, which reached to $z \sim 0.05$.

We learn something about the large-scale structure of the universe just from looking at redshift maps. Superclusters tend to be flattened pancakelike structures, or elongated filaments. Voids, by contrast, are more nearly spherical. Voids, by definition, have a very low density of bright galaxies. The density of nonstellar matter in voids is not always well determined. The transparency of intergalactic space places an upper limit on the density of dust: $\rho_{\text{dust}} < 4 \times 10^{-30}$ kg m^{-3}. The limits on Lyman alpha absorption by neutral gas in voids places a stringent upper limit on the density of neutral hydrogen: $\rho_{\text{H}} < 10^{-36}$ kg m^{-3}. However, the amount of ionized hydrogen and of dark matter in voids is not as well constrained.

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[7] The Sloan r band is centered at a wavelength $\lambda \approx 6160$ Å and is roughly comparable to the Johnson R band.