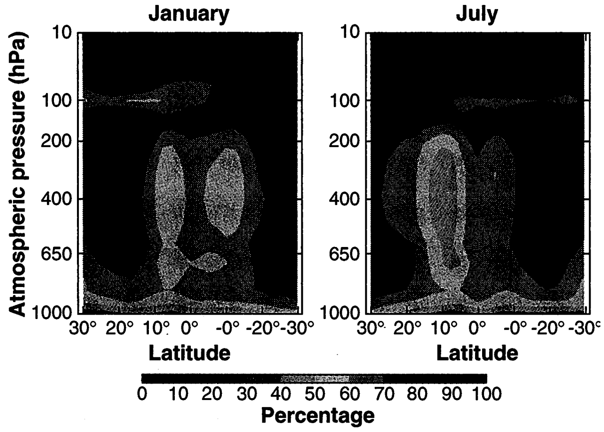
eled and observed temperature changes, rather than simple consideration of trends over a short (20-year) period. The NRC report draws the same conclusion (*3*).

Gaffen *et al.* (*2*) analyzed daily radiosonde data for the tropics, where the increase in lapse rate since 1979 has been most pronounced. These data, which are independent of the MSU data and almost independent of the surface data, show an increase in lapse rate since the late 1970s. Over the longer period from 1960 to 1997, however, they show a decrease in lapse rate. Brown *et al.* (*4*) obtained similar results using a different source of radiosonde data (*5*). They showed a widespread sharp decline in tropical lapse rates during the late 1970s, followed by an increase after the mid 1980s. One interpretation is that atmospheric circulation changes in the Pacific sector around the late 1970s (*6*), possibly a manifestation of the Interdecadal Pacific Oscillation (*7*), entailed changes in tropical lapse rate.



Controlling influences on air temperatures over the tropical oceans. Percentage of heating due to radiation for 1982 to 1994, based on diagnostics from (*16*). In regions colored blue, heat inputs are mainly convective. In regions colored red, they are mainly radiative. Convection dominates throughout the troposphere in the intertropical convergence zone. There is a rapid upward transition toward radiative control across the tropopause (at about 100 hPa) and, to a lesser extent, the trade wind inversions.

Gaffen *et al.* (*2*) found that lapse rate trends since 1979 have been greater on convectively more stable days, during which lapse rates are small, than on convectively less stable days, when further increases are limited by convective overturning. This is encouraging evidence for the high quality of the radiosonde data. Inversions, especially trade wind inversions, during which convection is inhibited by warmer air aloft, may respond to greenhouse gas forcing in a manner analogous to the tropopause. If so, then the air above the inversion would cool relative to the air below, because its temperature is controlled more by radiative than by convective equilibrium (see the figure). However, Gaffen *et al.* find that, for 1960 to 1997, the less stable days had the greater decrease of lapse rate. Resolution of this question requires both improved data and models that can fully simulate these inversions.

In contrast to Gaffen *et al.* (*2*), Angell (*8*) found more warming at the surface than in the troposphere since 1958, but a more limited station network was used in the study. Several recent papers (*9–12*) have stressed the need to improve radiosonde data availability and quality control and to apply physically based bias adjustments to retain valuable independence from MSU. This would improve on the method of Parker *et al.* (*5*), who used MSU as a reference. Hurrell *et al.* (*12*) lend support for the NRC panel's conclusions (*3*) by demonstrating the need for improved radiosonde and MSU data and for ongoing comparisons between analyses.

There are major physical differences between surface and tropospheric temperatures (*13*, *14*). Transport of heat by tropospheric winds ensures that variations of tropospheric temperature over continents and oceans are of similar strength. In contrast, if the winter atmospheric circulation in the Northern Hemisphere is stronger than usual, the inversions over the continents are weaker, and the continental surface can be much more anomalously warm than can occur over the oceans, where the high thermal capacity strongly damps any changes. The observation that nighttime temperatures have risen more quickly than daytime temperatures at the land surface (*15*) is consistent with a smaller tropospheric warming, because nighttime temperatures often relate to a very shallow layer (*3*, *12*, *15*).

The NRC panel considers that much of the discrepancy between surface and tropospheric temperature trends is real. Measurement errors and the effects of sampling natural variability account for the remainder of the discrepancy. The work of Santer *et al.* and Gaffen *et al.* reported in this issue made important contributions to the NRC Panel's findings. The consensus is that major advances are needed in our modeling and interpretation of temperature profiles, along with considerable improvements in data acquisition, documentation and distribution of the data, and their analysis by the scientific community worldwide.

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PERSPECTIVES: ASTRONOMY

Superclusters—the Largest Structures in the Universe?

Michael Drinkwater

The last two decades have seen a remarkable growth in our knowledge of the distribution of matter in the local universe. Large galaxy surveys have revealed structure on ever-increasing scales. The largest structures identified so far are conglomerates of thousands of galaxies with sizes of hundreds of millions of light-years. These superclusters may help define the largest scale of the initial density perturbations in the early universe and elucidate the early stages of galaxy formation. Until recently, however, this potential could not be realized because existing galaxy surveys were not large enough to contain a representative sample of superclusters. Several large galaxy surveys are about to close that gap by allowing the first quantitative measurements of large-scale structure on the scale of superclusters to be made.

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Galaxy surveys are normally based on two-dimensional optical images of the sky. To measure large-scale structure efficiently from the surveys, the third dimension of distance must be measured. This is usually the limiting step because it requires a detailed measurement of the spectrum of each galaxy. The first "large" three-dimensional galaxy surveys made in the 1980s were lim-

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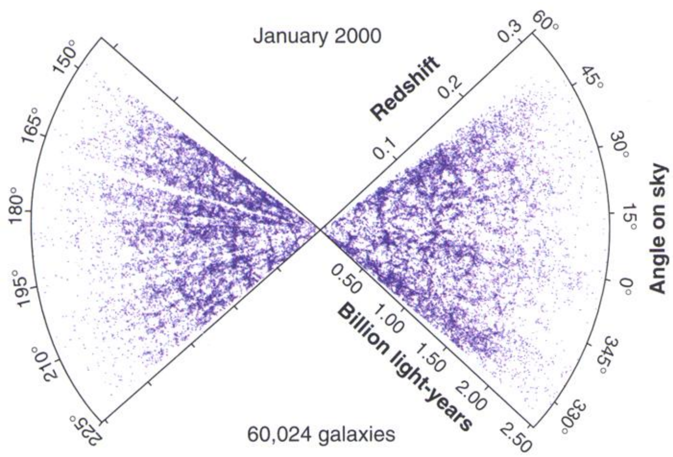
ited to samples of a few thousand galaxies and scales of only 100 million light-years, too small to identify superclusters. At that time, larger galaxy surveys were impractical, so a different approach was adopted. Instead of individual galaxies, galaxy clusters were used to trace the distribution of matter on larger scales. Galaxy clusters are well-defined, gravitationally bound systems of several hundred galaxies. A few hundred clusters cover the same volume as thousands of galaxies, but their distances can be measured in a fraction of the time. Studies of the distribution of galaxy clusters first revealed the presence of superclusters that could not be seen in the galaxy surveys (*1*). The cosmological implications of the large structures detected in these early surveys were seen at once: The popular models of galaxy formation at the time were not able to produce such large features (*2*).

Most recent observations of superclusters have continued to use galaxy clusters to trace the larger scale structure. One enormous structure, the Shapley Concentration, has a mass around 10^{16} times the mass of our own sun. Even at a distance of some 700 million light-years, its gravitational attraction has a substantial effect on our local group of galaxies, contributing perhaps 25% of our motion. A recent comparison of the density and size of the Shapley Concentration with theoretical models of structure formation has shown that such large structures can only form in a universe containing much less than the critical density of matter needed to halt the expansion (*3*).

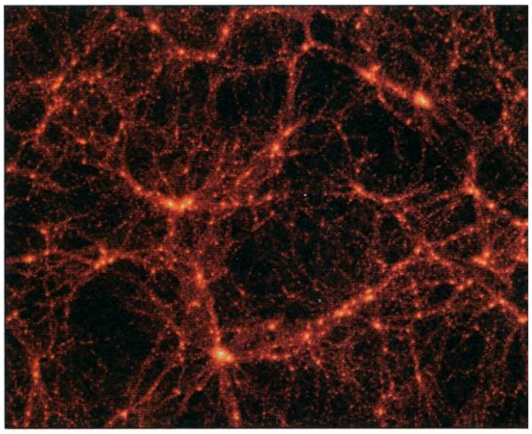
More remarkable than the mere existence of superclusters, and much harder to explain, are claims that their distribution is periodic. A compilation of some 300 galaxy clusters shows that the superclusters they define are in a lattice-like distribution with cells 430 million light-years in size (*4*). This work supports an earlier result from a narrow-beam galaxy survey that measured a periodicity of about 460 million light-years along a line of sight (*5*). The origin of this large-scale lattice is very hard to explain, and there is a concern that the use of the densest galaxy concentrations—galaxy clusters—to map out the large scales may exaggerate the appearance of the lattice. It is therefore preferable to measure all the individual galaxies in a sufficiently large volume of the universe. The best new galaxy surveys are, however, only just starting to probe supercluster scales.



The real universe. The distribution of galaxies in the partially completed 2dF Galaxy Redshift Survey (*9*). Only the newest galaxy surveys, such as the one shown here, will cover large enough volumes to identify and measure superclusters.

The very definition of superclusters is problematic because, unlike galaxies or even clusters of galaxies, they are not gravitationally bound. Theoretical models of the formation of large-scale structure suggest a different view of superclusters to their observational definition as very large groups of galaxies. The best models accurately reproduce the filamentary structures seen in real galaxy surveys (see the figure on the left). In these models, filaments form linking structures related to the initial density perturbations on very large scales. The models can extend to arbitrarily large scales and show that superclusters are simply higher concentrations of the filaments linking clusters (*6*). These large structures are seen in numerical simulations such as those by the Virgo Consortium (*7*) (see the figure, top right).

The real importance of superclusters will be felt when we have galaxy surveys large enough to make quantitative statistical measurements of their structure that can be compared directly with the theoretical simulations. Sensitive statistical approaches have been developed to describe superclusters, but existing surveys are not large enough to constrain the models significantly (*8*). The next wave of galaxy surveys uses large multiobject spectrographs that employ optical fibers to measure spectra of hundreds of galaxies at a time. The need for these facilities was clearly specified in these pages a decade ago (*2*). The 2dF Galaxy Redshift Survey on the Anglo-Australian Telescope (*9*) and the Sloan Digital Sky Survey (*10*) will be many times the size of the largest existing galaxy surveys and will probe the billion light-year scales needed to describe the supercluster population quantitatively.



Filaments in a model universe. This numerical simulation shows filaments of matter that can be identified with superclusters in a region of about one billion light-years across.

The optical surveys described above all miss about 30% of the sky obscured by dust in the plane of our own galaxy, the Milky Way. This region is known to include some superclusters and cannot be ignored in studies of nearby large-scale structure. Galaxies behind the plane of the Milky Way can be detected at radio frequencies not affected by dust. A full survey of the "zone of avoidance" defined by the plane of the Milky Way will shortly be completed with the use of new radio surveys at the Parkes and Jodrell Bank radio telescopes (*11*). This will complement the optical surveys to give us a complete picture of nearby superclusters.

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