appear to be turning subtly upward, suggesting that the cosmic expansion has been accelerating, at least in the epoch since $z = 1$. Even if one assumes that the mean mass density of the universe is much smaller than anyone believes, the data still seem to require the repulsive agency of a positive cosmological constant or some nonconstant dynamical property of the vacuum that simulates it in the present epoch.

Geometry and destiny

If one ignores, for the moment, anything more complicated than a cosmological constant, the observational evidence is best summarized in the parameter plane of Ω_Λ versus Ω_m, which are conveniently normalized, dimensionless measures of the cosmological constant and the present mean mass density, respectively. (See the figure on page 18.) Ω_m is ρ_0 divided by $3H_0^2/8\pi G$, the "critical" mass density required now to bring the Hubble expansion asymptotically to a halt after infinite time, in the absence of a cosmological constant. Ω_Λ is $\Lambda c^2/3H_0^2$.

The sum $\Omega_m + \Omega_\Lambda \equiv \Omega_T$ determines the spatial geometry of the cosmos in general relativity. If $\Omega_T = 1$ (the diagonal black line in the figure), space is flat on the cosmological scale. This flatness is, in fact, what the widely accepted "inflationary" version of Big Bang cosmology dictates. Above that diagonal, the cosmic geometry would be closed, like the surface of a hypersphere. Below it, we would have a geometrically open cosmos, with a negative curvature like that of a saddle.

When considering the possibility of a cosmological constant, it is important to distinguish between the spatial geometry of the cosmos and its *dynamical* fate. A geometrically closed universe can nonetheless expand forever, just as an open one can recollapse in a final Big Crunch. These two fates are divided by the purple line in the figure. At low mass density, any positive Ω_Λ forces the cosmos to expand forever. But above the critical mass density ($\Omega_m = 1$), the cosmological constant required for eternal expansion grows with increasing density.

Contours of confidence

How do the supernova observations constrain all this eschatological speculation? Fitting Ω_Λ and Ω_m to the Hubble plot of their 40 high-Z supernovae plus the lower-z Hamuy events, the Perlmutter group arrived at the region of the parameter plane inside the nested red ellipses that indicate various confidence levels. The dashed blue ellipses indicate the group's estimate of the worst-case scenario of maximal systematic errors all ganging up in the same direction. Schmidt and company have arrived at very much the same result, with slightly fatter ellipses because of their lower statistics. But their estimate of a possible sytematic error due to dust extinction is smaller than Perlmutter's.

Both groups conclude that the point ($\Omega_m = 1, \Omega_\Lambda = 0$), heavily favored until recently by most theorists, is strongly excluded by the fits. The theorists favored this point because they liked inflation and disliked the cosmological constant. If one continues to believe in inflation, the best fit on the $\Omega_T = 1$ diagonal is something like ($\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$), and the "deceleration parameter" $q_0 = (\Omega_m/2) - \Omega_\Lambda$ is clearly negative, implying that the Hubble expansion is in fact speeding up.

Theoretical aversion

Why have theorists shied away from the cosmological constant? Quantum field theory yields vacuum energy density terms on the order of the reciprocal square of the Planck length—10^{-35} meters. That corresponds to a cosmological constant more than 100 *orders of magnitude* larger than is permitted by the simple fact that we can see distant galaxies. For such enormous terms to yield a small sum, the argument goes, an absurdly improbable case of fine tuning—unless the cosmological constant is forced by some higher principle to vanish identically.

Theorists are also leary of temporal coincidence: If Ω_m is less than 1 now, it will get very much smaller as the universe continues to expand. At the same time, Ω_Λ will continue to grow. Is it plausible, they ask, that we just happen to be living in the brief epoch when the two competing cosmological parameters are comparable?

That's why speculative dynamical alternatives to a cosmological constant were much in evidence at the May Fermilab workshop. The negative pressure indicated by the supernova observations need not have the spatial and temporal constancy of Einstein's Λ. If it is due to something dynamical, like a tangle of light cosmic strings, a frustrated topological defect or a current epoch of mini-inflation, one can hope to find a good reason for its present level without invoking unseemly coincidence. "It would confront us with some really new and interesting physics," says University of Pennsylvania theorist Paul Steinhardt.[3]

An underdense universe

In the last few years, a variety of observations have been pointing toward an Ω_m well below 1, but not so small as to make nonbaryonic dark matter unnecessary. Neta Bahcall's Princeton group, for example, arrives at an Ω_m of about 0.3 by counting large clusters of galaxies as a function of redshift.[4] But getting a handle on Ω_Λ has been much more difficult. In fact, some cosmologists have used the low measured values of Ω_m as an argument against inflation, which requires that $\Omega_m + \Omega_\Lambda = 1$. That's one reason why the new high-z supernova results are receiving such attention.

The much anticipated MAP (Microwave Anisotropy Probe) orbiter, scheduled for launch two years from now, should be quite helpful in this regard. (See PHYSICS TODAY, November, page 32.) MAP will be particularly sensitive to the sum $\Omega_m + \Omega_\Lambda$. Thus it should nicely complement the supernova searches, whose greatest sensitivity is to the *difference* $\Omega_m - \Omega_\Lambda$, as one can see from the orientation of the confidence ellipses in the figure on page 18.

BERTRAM SCHWARZSCHILD

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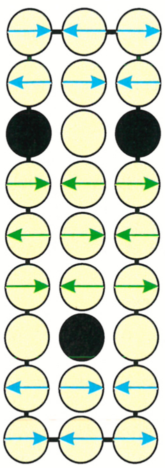
Are Stripes a Universal Feature of High-T_c Superconductors?

Do the spins and charges associated with copper and oxygen atoms in high-temperature superconductors arrange themselves in orderly rows in the copper oxide plane? Recent studies suggest that not just one but several families of the cuprates may feature such stripes, although in most cases the stripes are not static but fluctuate with time and position.

As if the superconducting copper oxides weren't mysterious enough, experiments within the past decade have revealed a magnetic structure—at least in members of the lanthanum strontium copper oxide family—whose period is different from that of the underlying lattice. One explanation that has attracted increasing attention is the possibility that stripe phases may form spontaneously when experi-



A MODEL OF CHARGE AND SPIN stripes. Pictured are the copper ions (yellow circles) in the copper oxide plane of a lanthanum strontium copper oxide superconductor. Not shown are the oxygen ions, which lie between adjacent pairs of coppers. The holes (black circles) are all located in the rows of charge and no spin (the third rows from the top and bottom), with the holes occupying every other copper site. The charge rows separate regions of copper ions whose spins align antiferromagnetically. (Adapted from ref. 1.)

menters dope these high critical-temperature (T_c) materials. According to this postulate, the added charges line up in rows in the copper oxide plane, sandwiching between them regions of copper atoms whose spins are aligned antiferromagnetically, with nearest neighbors having opposite spins. The repeat pattern of these spin regions is generally different from that of the crystal lattice, thus explaining the incommensurate peaks seen in diffraction studies.

The presence of some type of magnetic structure is not totally unexpected: It can be explained in terms of incommensurate spin fluctuations expected from a Fermi surface or interpreted as the antiferromagnetic spin fluctuations anticipated by some theories of high-T_c superconductivity. What's different about the stripe proposal is the assertion that not only the spin density but also the charge density is spatially modulated. One would expect charge order, which localizes electrons, to compete with conductivity. For example, charge stripes are seen in nickel and manganese oxides, cousins to the cuprates, but those materials are insulating (see the accompanying story on page 22).

The stripes seen in the nickelates and manganites are static features. By contrast, those that show up in members of the superconducting $La_{2-x}Sr_xCuO_4$ (LSCO) family appear to be dynamic stripes, which fluctuate in time and position. (The notation here indicates that the insulating material, La_2CuO_4, can be doped to any level by the addition of strontium atoms.) Indeed, until recently the only static stripes reported in the cuprates were in materials containing neodymium,[1] and then only for a doping level long known to produce a sharp dip in the critical temperature.

As long as incommensurate spin fluctuations were seen only in members of the LSCO family and in no other copper oxides, one could argue that it is the unique presence of stripes that keeps these materials from being better superconductors. Recent studies indicate, however, that LSCO may not be an exception after all. A neutron scattering experiment offers clear evidence that yttrium barium copper oxide (YBCO) materials also manifest magnetic structures suggestive of dynamic stripes.[2] Perhaps bismuth strontium calcium copper oxide (BSCCO) materials can be added to the list, if researchers have correctly interpreted the unusual behavior they see in angle-resolved photoemission studies of these materials.[3] These recent measurements on YBCO and BSCCO are compatible with *dynamic* stripes. There are also new reports of *static* spin-density waves even in superconducting materials with critical temperatures as high as 42 K.[4]

Some theorists are quite excited about the possibility of stripes, believing them to be intimately tied to superconductivity; others are intrigued by the stripes but skeptical that they are the key to zero resistivity; still others prefer a more conventional explanation for the data.

One model of stripes

One picture of stripes has been suggested by John Tranquada of Brookhaven National Laboratory and his colleagues from Brookhaven and the University of Tokyo, who have done numerous neutron scattering experiments using Brookhaven's High Flux Beam Reactor.[1] This group proposes a picture of static stripes in a tetragonal crystal of La_2CuO_4 doped with a ratio of one hole to every eight copper atoms. The figure above shows the arrangement of copper atoms (shaded circles) in a unit cell. The oxygen atoms (not shown) sit between every pair of neighboring copper atoms. The charge stripes—rows of holes (filled circles) alternating with copper ions—separate regions where the electron spins on the copper atoms are arranged antiferromagnetically. The period for the charge stripes is four lattice sites whereas that for the antiferromagnetic order is twice as much because the phase changes by π across each charge stripe.

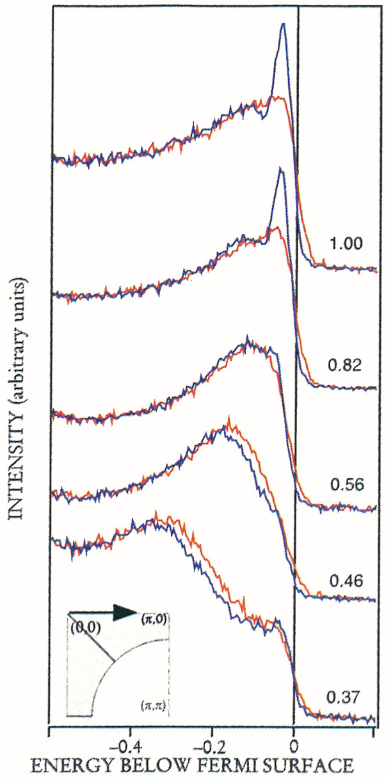
The first hints of stripe phases came from neutron scattering results in LSCO.[5-7] Neutrons can scatter off either the atomic nuclei comprising the lattice or the magnetic moments on the copper atoms. Thus, for undoped La_2CuO_4, which is an insulator with antiferromagnetic ordering of the copper spins, neutron scattering gives one peak in reciprocal space (the space associated with the wavevector k) corresponding to the average lattice spacing and one peak associated with the antiferromagnetic wavevector.

If there is a stripe structure superposed on the lattice, the charge order will show up as a splitting about the lattice peak (due to the small atomic displacements induced by the charge modulation). The magnetic order produces a similar splitting around the antiferromagnetic wavevector. Such splitting into incommensurate peaks around the position of the antiferromagnetic peak has been seen for samples of hole-doped $La_{2-x}Sr_xCuO_4$. Because the splitting was seen only when the neutrons scattered inelastically and not elastically, it was taken as evidence for dynamic, rather than static, spin fluctuations. To strengthen the case for a stripe phase, one would also like to see dynamic charge fluctuations—that is, fleeting correlations in the positions of the charges—which would be signaled by telltale incommensurate peaks about the reciprocal lattice points. So far, however, no such evidence for dynamic charge stripes has surfaced.

There is one rather anomalous material in which the stripe order appears to be static. The material is $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$, in which the addition of neodymium changes the lattice shape. Not only have researchers found static spin stripes in this material; they saw evidence for static charge stripes as well. The static charge peaks have been seen at a doping level of $x = 0.12$ in both neutron scattering[1] and x-ray scattering studies.[8] Studying samples with three different doping levels ($x = 0.12, 0.15, 0.20$), Tranquada and his colleagues have also reported[9] the coexistence of static stripes and superconductivity, albeit with T_c's below 15 K. A question remains, however, whether the samples might have had mixed phases, with some regions being superconducting and others manifesting stripe order.

Stripes in YBCO?

Various studies of YBCO have hinted at a stripe order, but until recently there was no clear evidence for the incommensurate peaks associated with spin fluctuations. Now Herbert Mook and his team from Oak Ridge National Laboratory and from the University of Washington, working on the High Flux Isotope Reactor at Oak Ridge, have reported promising data from neutron scattering experiments.[2]



PHOTOEMISSION SPECTRUM for a bismuth-based superconductor may contain a hint of stripe phases. Spectral curves taken above T_c (blue) and below T_c (red). Numbers labeling each curve represent the position in k space along the line from (0,0) to (π,0) (see inset). The blue curve falls below the red curve at low momentum values and rises above it at high values. The fractional difference in integrated spectral weight measured above and below T_c suggest a shift in spectral weight from low to high momentum. (Courtesy of P. J. White, D. L. Feng, C. Kim, Z.-X. Shen of Stanford University.)

Looking at the inelastic neutron scattering at temperatures well above T_c, the group saw a single peak at the position expected for the antiferromagnetic wavevector. As the sample was cooled, this peak began to split into two incommensurate peaks even above T_c. Upon further cooling, the central, commensurate peak declined in intensity while the two side peaks grew.

If the incommensurate magnetic structure for YBCO has the same orientation in k space as it does for LSCO, the displacement of the peaks seen in magnetic scattering should be the same. Mook told us that, although preliminary information would suggest that the magnetic structures are the same, a final determination is awaiting analysis of data obtained by using the new position-sensitive detector bank on the High Energy Transfer (HET) spectrometer at the Rutherford Appleton Laboratory in the UK.

And in BSCCO?

BSCCO superconductors have been studied by angle resolved photoemission, in which one measures the energy and momentum change between an incoming photon and an outgoing electron. In their studies of BSCCO,[3] Zhi-Xun Shen and his colleagues think they have found behavior that suggests stripe phases; such order had been predicted theoretically for BSCCO.[10] (Shen's collaboration includes researchers from Stanford University, the University of New South Wales, the University of Tsukuba and Japan's International Superconductivity Technology Center (ISTEC) in Tokyo.)

In angle resolved photoemission, one sits at a fixed point, corresponding to an electron with a particular momentum in the solid, and measures the intensity as a function of the electron energy. As the material goes superconducting and the superconducting gap opens, the edge of this spectrum typically pulls back from the Fermi surface and a sharp quasiparticle peak develops just below the Fermi energy. These features are apparent in the figure on this page, which shows the photoemission intensity as a function of energy at temperatures both above (red curve) and below (blue curve) T_c, for five values of wavevector k. The bismuth copper oxide sample had a T_c of 88 K, below the optimal value of 91 K.

Shen and his colleagues noticed something subtle about these curves: If you look at the curves for momentum values of $k = 0.37$ and 0.46 (in units of π/a), the intensity below T_c is less than that for temperatures above T_c. By contrast, at higher values of momentum (0.82 and 1.00), the intensity below T_c is larger. The net result is a shift in spectral weight from lower wavevectors to higher ones as a sample cools. Shen and his group have estimated the difference between the two wavevectors over which the spectral shift occurs and think that the difference is close to the reciprocal lattice spacing that charge order would have if stripes were present, although the error bars are large. No such shift is seen in an optimally doped sample.

Evidence for coexistence?

A Japanese–American collaboration has studied two types of materials in which static stripe phases appear to form even when the transition temperatures are relatively high. Members of the collaboration hail from Tohoku University in Japan and from Brookhaven National Laboratory and MIT in the US. In one neutron scattering study of $La_{1.88}Sr_{0.12}CuO_4$ grown at Tohoku University, this collaboration has seen incommensurate peaks in elastic scattering—evidence for a static spin order.[4] At the March meeting of the American Physical Society in Los Angeles, Kazuyoshi Yamada, who recently moved from Tohoku University to Kyoto University, showed that this static order appears to set in around 30 K, quite close to the T_c for this material. The collaboration has also studied $La_2CuO_{4+\delta}$, which is doped by the addition of oxygen rather than strontium. In preliminary data, taken on a sample with the intercalated oxygen occupying every fourth copper oxide layer and with a relatively high value of T_c (42 K), the researchers found that the static magnetic order and superconductivity appear to turn on at the same temperature.

Fans and critics

Reactions to the experimental evidence are quite varied. Some observers prefer to explain the incommensurate peaks in terms of a nested Fermi surface, a surface in which the same wavevector can connect a number of points. One would then expect a peak in the intensity of neutrons that scatter at just that wavevector. Others argue that it's unlikely that the Fermi surface would have just exactly the required topology to explain the observations in both LSCO and YBCO.

Andrew Millis (Johns Hopkins University) told us he won't be convinced that the experiments on high-T_c materials show charge–spin stripes as opposed to spin fluctuations until he sees more evidence that the spin structure has a large amplitude and that it is associated with a charge modulation. Specifically, he would like to see evidence for higher harmonics of the spin structure (indicating a sharp rather than gradual modulation of the spin density) or for peaks associated with charge modulation.

Philip Anderson (Princeton University) firmly believes the stripe phases occur, although he doesn't feel they are significant for superconductivity, especially as they anticorrelate with T_c. He feels that the materials form these ingenious stripes as a kind of macroscopically inhomogeneous phase intervening between the antiferromagnetic insulator at lower doping and the metallic phase at higher doping.

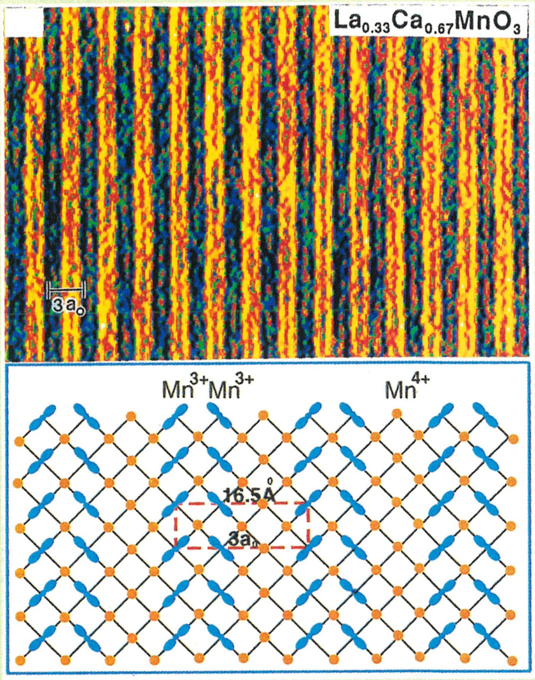
Shin-Ichi Uchida of the University of Tokyo told us that a number of his Japanese colleagues are a bit skeptical about the stripe interpretation. One of the criticisms is that there is no direct evidence for the one dimensionality implied by the simple model de-

Materials of a Different Stripe

The stripe phases in the copper oxide superconductors are rather fleeting structures. But stripes are solid features of related materials—nickel and manganese oxides—whose insulating phases feature a static ordering of charges. These other oxides are cousins of the layered lanthanum copper oxides, La_2CuO_4, all having the basic perovskite structure. They are generated essentially by replacing the copper atoms with other transition metals. Despite the similar structures, the behaviors of these materials are very different.

Many researchers who started out studying the copper oxides have subsequently turned to the nickelates or manganites, in part to gain additional insight into cuprate superconductivity. Interest has also been spurred by another phenomenon in the manganites: colossal magnetoresistance, or the huge change in resistance with magnetic field. The manganese oxides turn out to be particularly good materials in which to explore stripe phases because any charge ordering produces comparatively large lattice distortions, which are more easily seen than those in the other transition metal oxides.

A recent experiment revealed that manganese oxide has a more complex charge ordering than expected. Researchers from Bell Laboratories and Rutgers University got real-space images of the charge structure by using very high resolution (less than 3 angstroms), transmission electron microscopy. By imaging a single domain, the group found that two stripes form a stable pair, and these pairs repeat periodically.[1] (Actually, because the manganites are three-dimensional materials, these "stripes," or charge modulations in the manganese oxide planes, are really sheets, extending along a plane in the third direction.)



The micrograph shown here (for $La_{1-x}Ca_xMnO_3$ with $x = 2/3$) exhibits a regular array of paired, dark-blue fringes, separated by orange swaths. These pairs did not show up in earlier measurements on the same material (see PHYSICS TODAY, October 1996, page 19). They emerged only when the researchers took higher-resolution measurements. According to the microscopic model depicted below the micrograph, the doublet fringes were produced by electronic orbitals of adjacent Mn^{3+} ions (shown in blue) that were oriented perpendicular to one another. The sharing of electrons between the anisotropic orbitals of Mn^{3+} and its six oxygen neighbors caused a distortion of the lattice (due to the Jahn–Teller effect); the resulting strain produced the high-contrast blue regions in the images. The regions around the isotropic Mn^{4+} ions (shown in orange) were much less distorted and exhibited less contrast. The pairs stick together even when the doping level changes: Increasing the relative number of Mn^{4+} ions simply increases the separation between the Mn^{3+} pairs.

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picted on page 20. Uchida speculates that stripe order, seen to be harmful to superconductivity, may also weaken the spin gap, or normal-state gap.

Theoretical mention of stripe order actually preceded the experiments, as Steven Kivelson (UCLA) and Victor Emery of Brookhaven are careful to point out. Stripe order arose in a mean-field calculation as early as 1989, although in that case the system was an insulator.[11] Kivelson and Emery, together with Oron Zachar (UCLA), have proposed that the spin and charge stripes play a key role in high-T_c superconductivity.[12] As Kivelson sees it, if the charges were aligned in one dimension, they could in principle support either superconductivity or charge density waves, and the two compete; in static stripes, charge density waves win. However, if the stripes are dynamic, the fluctuations just might suppress the charge density wave, opening the door for superconductivity.

Douglas Scalapino (University of California, Santa Barbara) and Steven White (UCLA) have done some numerical simulations on the so called model with boundary conditions imposed on an 8×16 grid. They find that the charges and spins tend to separate into domains with a domain filling of 0.5 holes per site, consistent with experiments on the neodymium materials.[13] The static stripes at $x = 0.125$ suppress the pairing correlations. Feeling that a little stripe order just might be a good thing for superconductivity, but that too much can destroy it, Scalapino likens working with stripe order to "tickling the tail of the dragon."

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