radiation-driven wind results in two regimes (*6*, *7*). If the wind pressure exceeds the magnetic pressure, the field lines are open. We see this in the solar corona, where the solar wind streams away from the Sun into the interplanetary medium. Conversely, if the wind pressure is dominated by the magnetic pressure, the wind is magnetically confined; that is, it cannot leave the star. The surface where the two pressures are equal defines the magnetosphere. If the stellar magnetic field is dipolar, the magnetosphere has a toruslike shape. This torus is large: Its external radius may reach 10 stellar radii (corresponding to 40 solar radii or half of Mercury's orbit). If the star rotates, the magnetosphere rotates with it, as in a merry-go-round (see the figure).

Inside the magnetosphere, the (charged) atoms follow the field lines like beads on a string. They therefore inevitably collide in the equatorial region with atoms coming from the opposite direction. A strong shock develops, which heats the downstream gas to x-ray temperatures (several million kelvin). This superhot gas fills most of the outer part of the torus (*8*, *9*) (see the figure). The x-ray emission of several magnetic stars can be explained in this way, the latest one being the B-type star beta Cephei (*2*).

One important question was left unsolved, however. Radiation continuously drives particles into the magnetosphere, but they cannot accumulate forever. Havnes and Goertz (*6*) suggested that along the magnetic equator, where the field is weakest but the gas pressure strongest, the pressure equilibrium is unstable, and pockets of gas will be expelled, especially if the star rotates. Babel and Montmerle (*8*, *9*) discussed another possibility, namely that the equatorial gas eventually cools and somehow falls back on the star, thus recycling the wind material.

Smith and Groote now show how this material may return to the star (*1*). They have performed a detailed study of archival UV spectra of several magnetic B stars taken by the International Ultraviolet Explorer (IUE) satellite to test the idea put forward by Shore and Brown (*10*) that a magnetospheric torus could be detected via absorption lines in the star's spectrum. Smith and Groot argue for the presence of "clouds" with temperatures of 17,000 K, about one solar radius in size. The shape of the clouds is uncertain, likely a torus, as proposed by Shore and Brown, possibly flattened into a disk (see the figure). They further argue that at least some of the cloud material settles back to the star. Donati *et al.* also favor this conclusion (*2*).

Other phenomena take place as a result of the wind–magnetic field interaction. Because of wind shocks (and also perhaps because of the expulsion of magnetized gas pockets), electrons may be accelerated to high energies. Because they are embedded in magnetic field lines, they will radiate nonthermal radio waves, in addition to the usual thermal radio waves of the hot gas. This radiation has been detected in a number of cases with the Very Large Array (VLA). Trigilio and his collaborators (*3*) have developed a detailed three-dimensional model of a rotating, radio-emitting magnetosphere. They show how the periodic VLA emission can be explained and what the emission regions would look like if direct imaging were possible (see the figure).

These recent studies provide a wide variety of observational constraints on the magnetically confined tori around magnetic stars. New observations, such as detailed x-ray spectroscopy, magnetic field measurements, and multifrequency radio observations, will provide further important information. But the most promising future probably lies in detailed, three-dimensional modeling of the magnetized plasma and the wind dynamics, in particular to answer the biggest remaining question: Where has the wind gone?

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PERSPECTIVES: SUPERCONDUCTIVITY

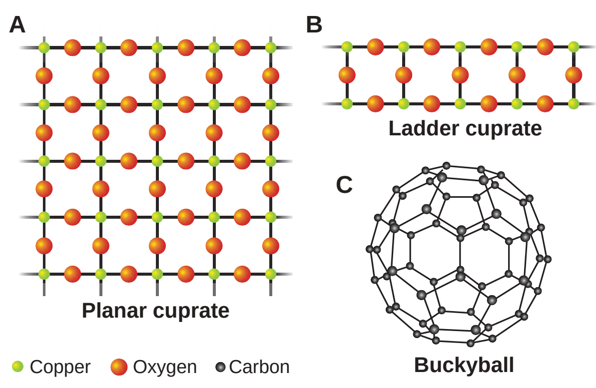
The Race to Beat the Cuprates

Elbio Dagotto

Superconductors are materials that lose all electrical resistance below a specific temperature, known as the critical temperature (T_c). Large-scale applications, for example, in superconducting cables, require materials with high (ideally room temperature) T_c's, but most superconductors have very low T_c's, typically a few kelvin or less. The discovery of a layered copper oxide (cuprate) with a T_c of 38 K (see panel A in the first figure) in 1986 (*1*) raised hopes that high-temperature superconductivity might be within reach. By 1993, cuprate T_c's of 133 K at ambient pressure had been achieved (*2*, *3*), but efforts to further increase cuprate T_c's have not been fruitful. Two reports by Schön *et al*. (*4*, *5*) in this issue—applying a similar technique to two very different materials—drastically alter the perception that planar cuprates are the only route to high-temperature superconductivity.

Enhanced online at www.sciencemag.org/cgi/content/full/293/5539/2410

Schön *et al.* use a field-effect device introduced in previous investigations to transform insulating compounds into metals (*6*). On page 2430, they show that copper oxide materials with a ladder structure (panel B in the first figure) can be superconducting (*4*), even without the high pressure applied in previous studies of related compounds. Even more spectacularly, they report on page 2432 that the T_c of a noncuprate molecular material, C_{60} (panel C in the first figure), known before to superconduct at 52 K upon hole doping (*7*), can be raised by hole doping with intercalated $CHBr_3$ to 117 K (*5*), not far from the cuprate record. Simple extrapolations suggest that the T_c could be increased even further, effectively ending the dominance of cuprates in the high-T_c arena.



The structures of superconductors. (**A**) Copper oxide plane, (**B**) copper oxide ladder, and (**C**) C_{60} molecule. Ladders of copper and oxygen atoms, as shown in (B), form spontaneously in some compounds.

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The idea behind the studies is conceptually simple. Field-effect doping exploits the fact that under a strong, static electric field, charge (electrons or holes) will accumulate at the surface of the material, effectively modifying the electronic density in that region. This is necessary to stabilize superconductors away from nominally insulating compositions. The dielectric portion of the field-effect device must be able to sustain electric fields large enough to induce a sufficient number of holes per atom or molecule for the material under study to become superconducting. In addition, the interface with the studied material must be as perfect as possible. Doping through a field-effect device (*4*, *5*) avoids imperfections that cause the system to deviate locally from its average properties. Such imperfections are inevitably induced by chemical doping. Disorder has not been seriously considered by most cuprate high-T_c theorists, but its important role is slowly emerging. Some phase diagrams of cuprates may have to be redrawn when doping is introduced through a field-effect device (*8*).

In ladder cuprates, electrons are more likely to move along the legs of the ladders, rendering the material quasi–one-dimensional. However, the ladder rungs are also very important: They induce an effective attraction between carriers, in this case holes, that leads to superconductivity (*9*). Superconductivity in a ladder material was first observed experimentally in 1996, when a T_c of 13 K was reported (*10*). However, the superconducting state was stabilized with a high pressure of about 3 GPa. Ambient pressure ladder superconductivity, although searched for extensively, was not observed until now.

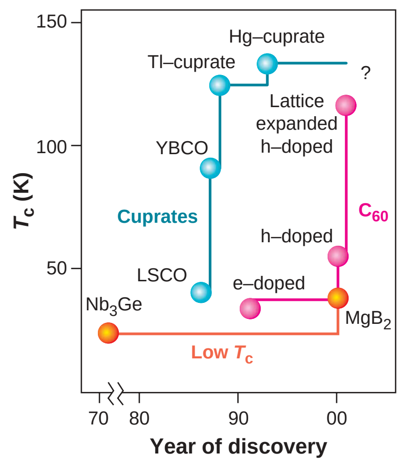
The previous negative results suggested that high pressure may transform the ladders into anisotropic two-dimensional systems (similar to the planar cuprates) by reducing interatomic distances (*11*). However, Schön *et al.* (*4*) show that ladders can become superconducting without high pressure, simply by a different doping procedure than previously used. Cuprate superconductivity is thus not unique to two-dimensional structures but exists in ladders as well, with similar copper and oxygen building blocks but a qualitatively different atomic arrangement.

The ladder compounds are conceptually important because they provide the only known superconducting copper oxide without a square lattice. The hypothesis that the ladder compounds are anisotropic two-dimensional systems appears difficult to sustain in view of the discovery reported in (*4*). Furthermore, the resistivity at optimal doping (when T_c is the highest) is linear with temperature (*4*). This behavior, observed also in nonsuperconducting ladders (*11*), was previously believed to be a unique signature of the exotic properties of high-T_c planar cuprates.

Crystalline C_{60} is normally an insulator, but in 1991, it was shown that electron-doped fullerenes are superconducting (*12*). Recently, the T_c in these compounds was raised to 52 K by field-effect hole doping, suggesting that T_c could be raised further by increasing the intermolecular distance—a quantity that was found to be almost linearly related to T_c (*7*).

The new results (*5*) confirm these expectations. It is widely believed that hole-doped C_{60} follows the standard model of superconductivity in which phonons (vibrations of the lattice and molecules) provide the source of attraction between carriers for pair formation and concomitant zero resistance. In fullerenes, high-energy intramolecular phonons are available to mediate the pairing. As the distance between molecules increases, the overlap of electronic wave functions decreases. As a result, the electronic bands narrow and the electronic density of states at the Fermi level (E_F) increases. These effects, supplemented by a substantial electron-phonon coupling (λ), appear to determine to a large extent the high value of the T_c. Smaller C_{36} fullerenes are expected to have a larger λ than C_{60} (*13*), suggesting another route to higher T_c's.

These arguments are persuasive and likely correct, but possible electronic pairing mechanisms should also be considered. Electron-electron interactions are characterized by an energy scale much larger than that of phonons and are more likely to generate high-T_c behavior. Intramolecular pairing of whatever origin—phononic or electronic—may produce the same local effective attraction, usually referred to as $-U$. Denoting by t the amplitude for electron hopping between C_{60} molecules, in simple models for superconductivity the reduction of t at fixed $|U|$ leads to an increase of T_c in weak coupling (*14*), as in the present experiments (*5*), where the hopping is regulated by intercalating small molecules. On the other hand, if T_c's of more than 100 K can be achieved in fullerenes with just phonons, then the relevance of phononic mechanisms for cuprates should be reconsidered. Has nature given us only one way to induce high-temperature superconductivity, after all?



Head-to-head race. T_c versus year of discovery for some superconducting materials. Orange, representative low-T_c compounds, which held the T_c record before cuprates and fullerenes were discovered. Magenta, representative planar cuprates. Light blue, representative fullerenes, with the highest T_c to date reported in (*4*).

Superconductivity in field-effect–doped materials is effectively two-dimensional, sandwiched between the undoped bulk material and the dielectric oxide. Is this effective lower dimensionality crucial for the high T_c obtained? Results for electron-doped fullerenes suggest otherwise—bulk- and field-effect–doped compounds have similar T_c's (*7*)—but the question is worth investigating. Correlating T_c with the electronic density of states at E_F would also allow for a more intuitive understanding of the results. The mechanism of increasing the density of states by reducing the bandwidth through the expansion of the lattice seems simplistic but appears to work. In theoretical studies of superconducting cuprates, band narrowing was caused by the antiferromagnetic background in which the holes are immersed (*15*). In this context, optimal doping is naturally associated with a peak in the density of states.

Through increasing the C_{60} lattice constant by 1% (*5*) or improvements of the field-effect device, it may be possible to induce a T_c above 133 K, the ambient pressure record for cuprates (see the second figure). However, the work on ladders (*4*) shows that cuprates can now also be doped by the field-effect device. An exciting organic versus inorganic race toward room-temperature superconductivity may be about to begin. If so, then field-effect doping will likely play a fundamental role.

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