contrasts of a few percent or more, which is ample to affect dynamics.

In view of all the complexities, how does one approach the question of why the outer planets have jet systems, long-lived ovals, and all the other observed richness of meteorological behavior? Cho and Polvani, in this issue (6), describe the behavior of an extremely idealized mathematical model and show that the model reproduces several features of the observed planetary circulations. The model represents a thin homogeneous "ocean" of depth H, on a planet of radius a, surface acceleration of gravity g, and rotation period P. It has no thermodynamic forcing and is initialized with a random velocity field. As Cho and Polvani discuss, other workers have studied similar models (7), but this is the first time that a series of experiments have been carried out for an unforced flow in full spherical geometry and for a range of parameter values spanning all the outer planets. The idea is to discover the key processes at work by isolating them in a very simple calculation.

The calculations represent extremely interesting fluid dynamical results. But what does one learn about the planets from qualitative agreement with observation in this model? The model has not been demonstrated to be unique in showing agreement, and therefore any conclusions must be tentative. One point of importance is the width of the jets that emerge. The model contains three scales: the planetary radius, the "deformation radius," and the Rhines scale. The deformation radius, from meteorology, is $L_D = \sqrt{gH}/\Omega$, where the rotation rate is $\Omega = 2\pi/P$. The Rhines scale (L_β) is given by $L_\beta = \sqrt{Ua}/\Omega$, where U is the magnitude of the flow speed. Rhines (8) has shown that in two-dimensional flow on a rotating sphere, an inverse turbulent cascade of energy to large scales is interrupted at scale L_β, and alternating jets can arise. The spacing of jets in the Cho and Polvani experiments, after initial transients, turns out to be on the order of L_β. But then, what sets the flow amplitude U on which the Rhines scale is based? This may depend on thermodynamics and remains an unanswered question. It is also possible that the new simulations are not based on the relevant deformation radius, and that the wrong regime, in terms of the ratio of L_β to L_D, is being explored. As Cho and Polvani point out, it is not at all clear what value of L_D (if any) is appropriate to simulate the correct planetary dynamics in a two-dimensional model.

But if the Cho and Polvani calculations have indeed captured the essential physics of jets and eddies on the outer planets, then the thermodynamic complexities described above for deep atmospheres are incidental, and fluid dynamics controls the gross structure and the visual appearance of the outer planets. If true, this would be a striking conclusion, simultaneously simplifying and complicating. The fluid dynamics is turbulent and nonlinear, yet leads to highly organized and persistent mean flows.

The simulations do not produce eastward currents at low latitudes on Jupiter and Saturn. Observations show strong eastward equatorial jets, which are particularly puzzling because they represent concentrations of angular momentum (more rapid rotation than the average). An angular momentum pumping process is needed to maintain them. Because these jets are on the equator, they cannot be produced by poleward drift of gas that conserves angular momentum, the way eastward mid-latitude jets on Earth can be produced. As Cho and Polvani remark, the fact that none of their numerical experiments produces these jets suggests that another mechanism, beyond the scope of the simple model, may be necessary. Stratification and the third dimension might be the missing ingredients.

Future progress will depend on new information from the planets. Numerical modeling has become very powerful, but the physical system is so ill-defined that modeling is not well constrained. It would be useful to have detailed maps of velocity fields within Jupiter's clouds, so that statistical properties could be compared with numerical simulations. The NASA Galileo orbiter may obtain such data during the next 2 years. It would also be useful to have more probes beneath the clouds of the outer planets, to better define the depth and the stability properties of the flows.

References and Notes

1. A. P. Ingersoll, *Science* **248**, 308 (1990).
2. The first set of reports on the NASA Galileo Jupiter entry probe measurements appeared in the 10 May 1996 issue of *Science*.
3. J. R. Holton, *An Introduction to Dynamic Meteorology* (Academic Press, New York, 1992).
4. T. Guillot, D. Gautier, G. Chabrier, B. Mosser, *Icarus* **112**, 337 (1994).
5. B. J. Conrath, P. J. Gierasch, E. A. Ustinov, paper presented at the XXI General Assembly of the European Geophysical Society, The Hague, Netherlands, May 1996.
6. J. Y.-K. Cho and L. M. Polvani, *Science* **273**, 335 (1996).
7. For example, T. E. Dowling and A. P. Ingersoll, *J. Atmos. Sci.* **46**, 3256 (1989); P. S. Marcus, *Nature* **331**, 693 (1988); G. P. Williams, *J. Atmos. Sci.* **35**, 1399 (1978).
8. P. B. Rhines, *J. Fluid Mech.* **69**, 417 (1975).

Cuprates Fall into a Gap

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Superconductivity occurs in a metal when it is energetically favorable for the electrons to form Cooper pairs. Pair formation causes an energy gap to open in the electronic spectrum. The pairs may be destroyed in the presence of photons or thermal fluctuation energy, but only if the incident energy exceeds the energy gap. Therefore, the gap is a measure of the robustness of the superconducting state: The larger the gap, the higher the critical temperature T_c. A decade after the discovery of high-temperature superconductivity in the cuprates, persuasive evidence has been obtained for a partial gap that opens, not at T_c, but at a temperature 100 to 150 K higher. Is this higher temperature gap flagging the existence of an exotic electronic phase or merely a harbinger of superconductivity itself? How does the newly discovered gap affect the debate on the nature of electronic excitations and the origin of superconductivity in these remarkable solids? These and other issues continue to roil the field. In this issue, Loeser *et al.* (1) report photoemission spectra that bring this higher gap into sharper relief.

In a photoemission experiment, electrons are ejected when the sample is exposed to photons. In the more sophisticated technique of angle-resolved photoemission spectroscopy (ARPES), only the electrons ejected in a prescribed direction are detected (see figure). This refinement enables the energy versus momentum dispersion within the sample to be determined directly if it is two-dimensional (2). The Fermi surface (the surface enclosing all the occupied states) may be mapped by changing the detection angle.

The essential structure in all superconducting cuprates is the copper oxide layer. In the parent compound of each family, the highest $3d$ state in each copper ion is occupied by a single electron. In principle, a lattice with one electron per site should be a metal with a half-filled band. However, in the cuprates, Coulomb repulsion between two electrons on the same site is so strong that electron hopping and band formation are precluded altogether: The parent compound is an insulator. Dramatic changes occur when a small fraction of the electrons are chemically removed to create vacancies or

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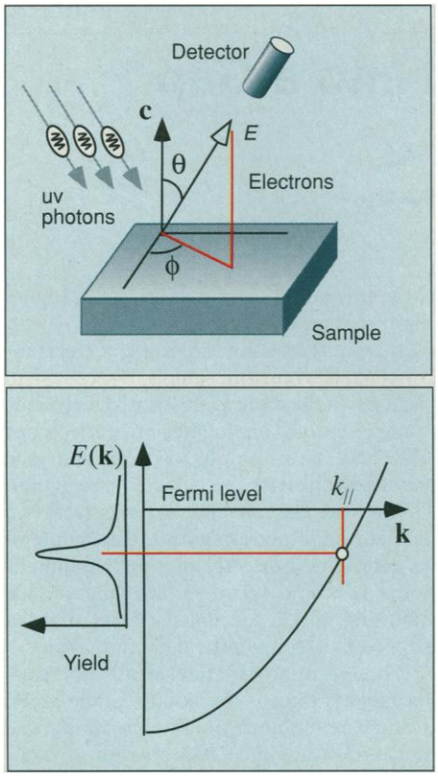
holes (doping). Because the holes can move freely without forcing two electrons onto one site, the insulator readily converts into a metal. This picture was confirmed by early Hall effect experiments (*3*), which showed that the mobile charge is positive and equal in density to the vacancies created by chemical doping. When the vacancy fraction exceeds 10%, superconductivity appears. With increasing hole density, T_c increases rapidly (underdoped phase), attains a maximum (in the optimum range 17 to 20%), and then falls to zero beyond 20% (overdoped).

ARPES has been used extensively by Olson, Shen, and others (*2*) to map the Fermi surface of the optimally doped cuprates. Although the Fermi surface obtained is in nominal agreement with band calculations, other features in the spectra have not been as easy to interpret. In general, an electron in a metal sees the Coulomb force of all the other electrons. As it moves, it is surrounded by an attendant cloud of excitations. In the familiar metals, however, these excitations are very effective in shielding the electron's charge, so that the moving entity behaves as an independent (quasi) particle that is long-lived. It appears in the ARPES as a narrow peak (see figure). Anderson and others have argued that, given the strong interaction in the cuprates, this quasi particle picture breaks down (*4*). In cuprates, the spectral peaks, when they are resolved, are anomalously broad (*1, 2*). More significantly, the spectral weight is distributed over a large, featureless background (the background is much smaller in conventional metals). The resistivity and Hall effect above T_c are also quite unlike those observed in typical metals (*3*).



In ARPES, detection of ejected electrons is restricted to a selected direction (fixed by θ and ϕ) (upper panel). The lower panel shows how the dispersion curve, $E(\mathbf{k})$ versus $\mathbf{k}$, is related to θ and the final kinetic energy E. For a two-dimensional sample, the momentum of the initial state $k_{||}$ equals $k_f \sin\theta$, where k_f is the final momentum. In conventional metals, the photoemission spectrum (yield) is sharply peaked around the value of the kinetic energy E that corresponds to $E(k_{||})$, as shown.

As we move from the optimum, through the underdoped phase, to the parent insulator, a more serious problem arises. In the insulating limit, the Fermi surface must vanish. Yet a theorem of Luttinger's states that its volume remains unchanged by interaction. How does the Fermi surface accomplish this disappearing act? About 5 years ago, evidence began accumulating for a partial gap opening in underdoped cuprates at a temperature T_s about 100 to 150 K higher than T_c.

A way to probe the density of states in a metal is provided by nuclear magnetic resonance. The nuclear spins may be driven out of equilibrium by a tipping pulse. The time they take to relax back to alignment with the external field (T_1) depends on the phase space of the electrons (which act as a spin bath). Expressed in the form $1/T_1T$, the relaxation rate is proportional to the square of the electronic density of states at the Fermi level. For the copper nuclei in YBaCuO, however, the observed rate is not only much larger than expected, but also strongly temperature-dependent (*5*). More surprisingly, in underdoped YBaCuO, the rate rises to a broad maximum at the temperature T_s, and then falls with cooling (*5*). Rice first proposed in 1991 that the downturn could be understood if a "spin-gap" opened at T_s in the electronic spectrum, reducing the phase space available to the relaxing nuclear spins (*6*). Soon after, Loram *et al.* confirmed a downturn in the density of states extracted from high-resolution heat capacity measurements on underdoped samples of YBaCuO, starting near T_s (*7*). (Because the sample remains metallic below T_s, the gap removes only a fraction of the states at the Fermi level; many researchers prefer to call it a pseudogap.) In underdoped YBaCuO, the pseudogap has also been shown to affect the resistivity measured in the layer (*8*) and the infrared conductivity parallel to the *c* axis (normal to the layers) (*9*). The pseudogap hindering the *c*-axis conduction has been observed to decrease measurably in a magnetic field (*10*). The effect is almost independent of the field direction, suggesting that gap formation depends sensitively on the spin degrees of freedom.

What causes the pseudogap? In 1988, Fukuyama and others (*11*) proposed a phase diagram based on an extension of the resonating valence bond model (*12*). In the underdoped region below T_s, a new electronic phase in which (only) the spins form singlet pairs appears. However, the sample remains nonsuperconducting until Bose condensation of the charge degrees occurs at a lower T_c. With increased doping, the interval between T_s and T_c shrinks, until at optimum doping the spin-singlet phase disappears (in qualitative agreement with the observed behavior of T_s with doping). However, many issues are unresolved. Why is the downturn in $1/T_1T$ seen only in the bilayer cuprates? Ubbens and Lee (*13*) suggest that coupling between spins in adjacent layers of a bilayer cuprate is essential for stabilizing the singlet phase. A spin-singlet state also appears in the interlayer model of Anderson. Other theorists forsake spin-singlets altogether and interpret the pseudogap as just the superconducting gap. Because of thermal fluctuations, the supercurrent response does not appear until T_c is reached. As shown by Loeser *et al.* (*1*), ARPES provides detailed information, such as the $\mathbf{k}$ dependence of the pseudogap around the Fermi surface, that should discriminate between the competing models. With measurements of increased sophistication, we may anticipate answers to many of the above questions, especially the puzzle of how the Fermi surface vanishes in the insulating limit.

References and Notes

1. A. G. Loeser *et al.*, *Science* **273**, 325 (1996).
2. For a review, see Z. X. Shen and D. S. Dessau, *Phys. Rep.* **253**, 1 (1995).
3. N. P. Ong *et al.*, *Phys. Rev. B* **35**, 8807 (1987); For a recent review, see N. P. Ong, J. M. Harris, Y. F. Yan, in *High T_c Superconductivity and the C_{60} Family*, S. Feng and H. C. Ren, Eds. (Gordon and Breach, Newark, NJ, 1995), p. 53.
4. P. W. Anderson, *Phys. Rev. Lett.* **67**, 660 (1991); *Science* **256**, 1526 (1992); *ibid.* **268**, 1154 (1995).
5. H. Yasuoka *et al.*, in *Strong Correlation and Superconductivity*, H. Fukuyama, S. Maekawa, A. P. Malozemoff, Eds. (Springer-Verlag, New York, 1989) pp. 254; R. E. Walstedt *et al.*, *Phys. Rev. B* **41**, 9574 (1990); M. Takigawa *et al.*, *ibid.* **43**, 247 (1991); H. Alloul *et al.*, *Phys. Rev. Lett.* **67**, 3140 (1991).
6. T. M. Rice, in *The Physics and Chemistry of Oxide Superconductors*, Y. Iye and H. Yasuoka, Eds. (Springer-Verlag, New York, 1992), p. 313.
7. J. W. Loram *et al.*, *Phys. Rev. Lett.* **71**, 1740 (1993).
8. T. Ito, K. Takenaka, S. Uchida, *ibid.* **70**, 3995 (1993).
9. C. C. Homes *et al.*, *ibid.* **71**, 1645 (1993).
10. Y. F. Yan *et al.*, *Phys. Rev. B* **52**, R751 (1995).
11. Y. Suzumura, Y. Hasegawa, H. Fukuyama, *J. Phys. Soc. Jpn.* **57**, 2678 (1988); *Physica C* **153-155**, 1630 (1988); N. Nagaosa and P. A. Lee, *Phys. Rev. Lett.* **64**, 2450 (1990).
12. G. Baskaran, Z. Zou, P. W. Anderson, *Solid State Commun.* **63**, 973 (1987).
13. M. Ubbens and P. A. Lee, *Phys. Rev. B* **50**, 438 (1994).

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