

Although originally developed for ^3He , Landau's theory has made an even greater contribution to understanding electronic liquids in metallic solids. Its predictions account for the properties of a vast number of metals, but researchers have discovered in recent decades some special materials that, although metallic, do not conform to the theory. These have become known as non-Fermi liquids, and the possible origin of such states has become the subject of intense research (8).

One known source of non-Fermi liquid behavior is proximity to a quantum critical point (QCP). This is a point where the system undergoes a continuous zero-temperature phase transition, as a function of some non-thermal tuning parameter p (which could be pressure, magnetic field, chemical doping, etc.) (9). Such transitions are often driven by competition between two types of interaction that favor different ground states, the balance between them being altered by tuning p . Around the QCP, in a region that can extend up to rather high temperatures, the properties of the metal are rendered anomalous by the presence of strong fluctuations between the competing states.

A much-studied realization of this phenomenon is in the heavy-fermion compounds (2). In these materials, f-electrons on rare-earth ions have a strong tendency to localize, while the remaining outer electrons form a conduction sea distributed throughout the material. Thus, the system is essentially a Fermi liquid interacting with localized spins, and two effects compete for dominance (1, 10).

One is the Kondo effect, which occurs when the conduction sea screens the spin of each rare-earth ion as the temperature is lowered (see the figure). At low temperatures, the resulting state is a "heavy Fermi liquid"—a state that obeys Landau's theory, but with a quasi-particle effective mass up to a thousand times that of the bare electron.

The second competing interaction is the Ruderman-Kittel-Kasuya-Yosida (RKKY) effect. Neighboring spins interact via waves in the conduction sea, tending to make them align or anti-align depending on the details of the crystal structure. The resulting state is an ordered magnet, with the local moments on the rare-earth ions coupled only weakly to the conduction sea.

Neumann *et al.* report something truly remarkable: the observation of this competition, complete with QCP, in a system actually made from ^3He atoms. They created a two-dimensional bilayer, with the upper layer playing the role of the conduction sea and the lower layer roughly that of the spins. In this case, coverage (the total two-dimensional density of

^3He atoms in the bilayer) is the tuning parameter p . The low-coverage state appears to be a single-component Fermi liquid, analogous to the heavy Fermi liquid in the traditional case. The high-coverage state consists of two decoupled layers, one of which is in some way magnetic (11) while the other forms a Fermi liquid, analogous to the magnetically ordered state in the rare-earth version.

Although the main achievement of Neumann *et al.* is to bring non-Fermi liquid physics back to the prototype Landau system in ^3He , perhaps the most intriguing feature of their data is an intervening phase that cuts in at coverages before the QCP is reached. This is tantalizingly reminiscent of the phases that mask QCPs in solid-state examples: superconductivity in several of the heavy-fermion compounds (12, 13) and the as-yet-unidentified phase in $\text{Sr}_3\text{Ru}_2\text{O}_7$ (14, 15). Many possibilities now exist for texturing and self-organization of correlated fermions at low temperatures. If characterization of this intervening phase can be accomplished, giving an example of novel phase formation in an uncharged atomic system, we will have taken another major step toward understanding the subtle physics that underlies a rapidly developing field.

GEOCHEMISTRY

"C"ing Arctic Climate with Black Ice

Richard B. Alley

New ice-core measurements suggest that soot influenced recent Arctic climate change.

Humans have put our sooty foot in a lot of places, leaving visible tracks with consequences. On page 1381 in this issue, McConnell *et al.* report a new way to see those tracks, finding them bigger, blacker, and more influential than we thought (1).

Climate scientists are now confident that business-as-usual fossil-fuel burning for another century or two would lead to substantial global warming in response to increased atmospheric carbon dioxide (CO_2) concentrations. However, it is more difficult to project the climate of the next decade, and it has only recently become possible to confidently attribute most of the changes over the past century to specific causes. This is because the

The author is in the Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA. E-mail: rba6@psu.edu

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11. Strictly speaking, long-range magnetic order cannot occur in two dimensions at nonzero temperature. However, the tendency to such order can still manifest itself through "metamagnetism" (nonlinear features in the field-dependent magnetization). The QCP is nonetheless well defined, because a zero-temperature ordered state remains possible.
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CO_2 forcing of the past century, and the additional forcing of the next decade, are of the same order of magnitude as many other natural and human effects (2).

In particular, the effects of airborne particles (aerosols) introduce large uncertainties into climate-change attributions (2). Most aerosols cause net cooling, partially offsetting greenhouse-gas warming, but black carbon (or soot) tends to warm the atmosphere, especially by lowering the very high reflectivity of snow. The short-term reduction in warming achievable by reducing soot emissions may help to avoid dangerous human influence on the climate (3).

Has soot contributed to past climate change? In the early 20th century, the Arctic warmed more strongly than anywhere else on Earth (4); was this natural climate variability, or might human soot have contributed?

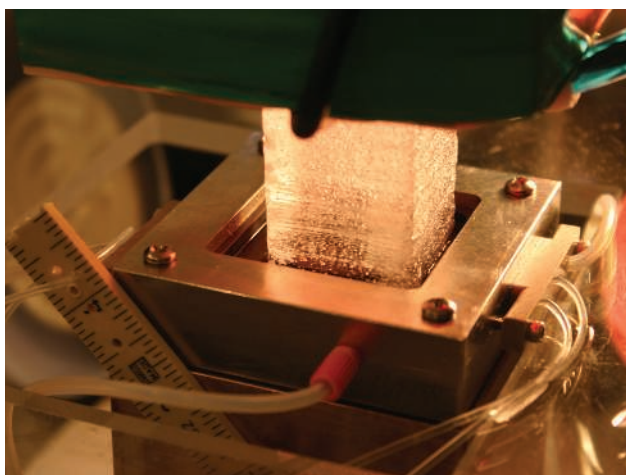
Unfortunately, modern instruments did not sample black carbon until recently. Investigators have relied on models and estimates of various combustion sources and efficiencies to constrain the effects of soot. McConnell *et al.* now report a detailed history of black carbon and its sources, extracted from a Greenland ice core, that goes a long way toward answering these questions.

A quiet revolution over the past decade has transformed many ice-core analyses. Once, trace chemicals in ice were determined by laboriously cutting, cleaning, and analyzing individual ice samples; now, clean melters feed streams of ice-core-derived water to a suite of instruments for continuous analyses. McConnell *et al.* used such an automated process (see the figure) to analyze a recently recovered core from a central-Greenland site where large amounts of snow accumulate every year. They obtained highly accurate, well-dated chemical histories—including black carbon concentrations—from 1788 to 2002, with a time resolution of less than a year.

For the first 60 years of the record, black carbon concentrations remained relatively stable, but the period from 1850 to 1951 showed highly elevated soot concentrations, especially during winter, when peak values were 10 times higher than the baseline. Lower values (although still higher than before 1850) mark the last 50 years of the record. Comparison to selected sections of a second core, collected 350 km to the south, shows close agreement, demonstrating the regional coherence of the signal.

Thus, black carbon concentration rose greatly to a peak in Greenland and still remains somewhat elevated. What was responsible? McConnell *et al.* were also able to detect low concentrations of organic molecules. They focused on vanillic acid, which originates largely from the burning of coniferous trees. Before 1850, soot and vanillic acid were highly correlated, especially during the summer fire season. Around 1850, when soot levels rose, correlation to the forest-fire indicator was lost, especially during winter. Instead, the higher soot values correlated closely with an acid-rain indicator (non-sea-salt sulfate, after exclusion of the well-known sulfate spikes from large volcanic eruptions). The human fingerprint is clear.

McConnell *et al.* even traced the soot to its source. Using the instrumental weather record for 1958 to 2002, they identified the main snowfall events for their site. Adopting a typical residence time for atmospheric particles, they then looked back along the trajectories of the precipitating air masses, finding the primary source region in eastern North America.



History in the making. A section of an ice core is melted in the clean laboratory for the report by McConnell *et al.*; meltwater from only the central part of the sample is diverted to the analytical line.

They infer a similar source for older samples by analogy, although circumstantial evidence points to increasing importance of an Asian source as North American emissions decreased after 1951.

Thus, a natural biomass-burning source of soot, primarily in summer, was overwhelmed by a fossil-fuel-burning source, primarily in winter, for a carbon-blackened century beginning about 1850. Since 1951, a weakening human signature may reflect technological advancement leading to cleaner combustion in eastern North America.

Do these observations help us understand climate history? Recent attempts to assess the climatic effects of black carbon, especially in the Arctic, have been largely restricted to the short interval of reliable instrumental records. McConnell *et al.* calculated the effect of their measured soot on absorbed solar radiation at their Greenland site. Based on comparison to an analysis for 1998 and 2001 for the whole Arctic (5), they then estimate the whole-Arctic effect of soot since 1788.

Changes in absorbed solar radiation are unimportant in the dark Arctic winter, and peak during early summer, before seasonal snow melts away to reveal darker surfaces less affected by soot. Focusing on that most sensitive season, McConnell *et al.* estimate an average Arctic warming effect from soot of more than 1 W/m^2 between 1850 and 1951, peaking in 1906 to 1910 at more than 3 W/m^2 —eight times the natural forcing. For comparison, the globally and annually averaged forcing from the total anthropogenic CO_2 increase in the year 2006 was $\sim 1.7 \text{ W/m}^2$ (2). For regional and seasonal changes, the soot effects must be important.

20th-century Arctic warming arrived in two sharp ramps (6): a late-century rise that

paralleled the global response to greenhouse-gas increase, and a similarly strong early-century rise of more obscure origin. Processes in the Arctic, such as the ice-albedo feedback, tend to amplify natural variability (7) and the response to some forcing. The broad correspondence between the soot peak and the earlier observed warming suggests that the Arctic changes in this case may also be amplified, because the forcing was stronger in the Arctic than elsewhere.

Greenland is not the whole world, and more records (8) and modeling will be needed to establish whether soot was important in the early-20th-century Arctic warming. But the results of McConnell *et al.* place much tighter constraints on the history of soot forcing of Arctic climate and should reduce uncertainties in climate-change attribution. The rise and fall of soot in Greenland illustrate the human ability both to alter our environment and to limit those alterations.

The instrumental virtuosity and the richness of the ice-core record promise additional discoveries: today black carbon and vanillic acid, but what about tomorrow? At a recent meeting, I was asked whether big questions still remained to be solved in ice-core science. As shown by McConnell *et al.*, the answer is an unequivocal yes.

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