# First light on fluid carbon

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RESEARCHERS at the University of Texas, Austin, may have caught the first, fleeting glimpse of fluid carbon. D. H. Reitze, H. Ahn and M. C. Downer describe in *Physical Review* (B**45,** 2677–2693; 1992) how both graphite and diamond can be melted momentarily by intense laser irradiation before expanding as a hot plasma.

The liquid phase of the element carbon is elusive, as it appears to exist in equilibrium only at temperatures of about 5,000 K and at pressures above several hundred atmospheres. The phase cannot be contained in any vessel, because all other materials melt or chemically react before the temperature required for the liquid state of carbon is reached. Clearly the structure of this state is of interest to those studying condensed matter physics, but because these conditions can be found in planetary interiors, it is also important for geophysics and astrophysics.

The first evidence for this phase came from experiments using pulsed ohmic heating of graphite electrodes. Shock-wave studies and pulsed-laser heating of graphite and diamond have also been tried (see F. B. Bundy's review in *Physica* **156**A, 169–178; 1989). Downer and colleagues used laser pulses lasting less than a picosecond ($10^{-12}$ s) in their new experiments, both to create and to probe their fluid carbon.

It is well known that short, intense laser pulses are capable of turning any substance into a high-temperature, high-density plasma. By careful control of the energy fluence in the pump pulse it is possible to determine a threshold for melting as the first stage in the process of plasma formation. A second, probe pulse will be reflected or will generate second-harmonic (or frequency-doubled) light, and the change in either of these can be followed as a function of the pump fluence, the time elapsed, and the wavelength, polarization and angle of incidence of the probe. This parameterization gives detailed information on the changes in electronic structure of the surface layer to a depth equal to the optical absorption depth and permits the determination of the material's dielectric function $\varepsilon(\varpi)$. Several detailed experiments with pico- and femtosecond pulses have been performed on silicon and gallium arsenide, as well as several metals over the past decade.

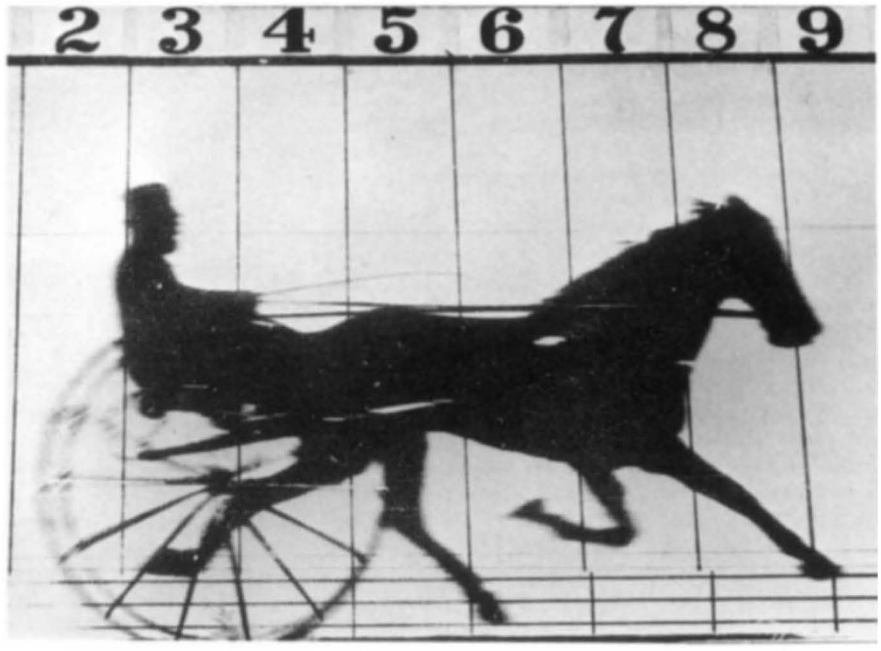
The pump–probe experiments of Downer and colleagues with a temporal resolution of about 0.1 ps reveal a sharp transition to a high-reflectivity phase at visible wavelengths, above a threshold, $F_m$, of the pump fluence. For graphite, $F_m = 0.13$ J cm$^{-2}$; and for diamond, $F_m = 0.63$ J cm$^{-2}$. What happens is that the pump pulse increases the number of mobile charge carriers in the graphite and then heats this electron plasma. This is confirmed by detailed analysis of the dielectric function for fluences below $F_m$.

Because the probe laser sees the electron plasma, not the state of the carbon ions, an indirect argument is needed to suggest that a fluid state of carbon is created. Indeed, for pump pulses above $F_m$, the phase transition initially is an electronic one, as it seems unlikely that there is enough time in the 0.1-ps pulse duration for the lattice of carbon atoms to be heated to the same temperature as the electron plasma. Instead, possibly a hot electron plasma coexists with relatively cold atoms. Although many of the electronic bonds responsible for graphite's rigid structure will have been broken, the atoms may still have a relatively small kinetic energy and have not yet had enough time to form the liquid phase. But in about 0.5 ps, thermal equilibrium may have been established between the hot electrons and the lattice, at which point the material will have become fluid.

The high reflectivity of the material lasts for a few picoseconds, but then drops. This is because of the expansion of the hot fluid, originally as dense as the graphite, into a rarefaction wave, during which the carbon–vacuum interface moves with a velocity in excess of the speed of sound. After 10 ps, the sharp boundary of the graphite is smeared over a distance comparable to one quarter of an optical wavelength (about 0.1 μm), and the resulting gradient in refractive index reduces the reflectivity. Such effects have been seen previously with silicon and gallium arsenide heated above their critical points.

In diamond, the electron plasma is created by a three-photon absorption process across the large band gap between valence and conduction bands. This process requires a higher irradiance, which explains the higher threshold value of $F_m$. The diamond becomes opaque and the electronic structure appears to make a transition to the same fluid phase as observed with

## Snap judgements




THIS remarkable photograph was taken by a remarkable man, Eadweard Muybridge, a pioneer of sequence photography. Muybridge — born Edward Muggeridge (he changed his name), died Eadweard Maybridge (a misspelling on his tombstone) — was English by birth but in 1851, at the age of 21, moved to the United States where he gained a high reputation as a photographer. Among his commissions was one from Leland Stanford, a former governor of California, to photograph a trotting horse and settle the controversy as to whether all four hooves are lifted off the ground at the same time. The answer, revealed by images such as that reproduced here, was that they are. The work of Muybridge and others is celebrated in a exhibition which opened this week at the Museum of the Moving Image in London. Entitled "Catching the Action: Muybridge and the Chronophotographers", it runs until 31 May. **T.L.**