after the reversal, poles which they call near-transitional (see also ref. 8). They test whether these pairs are antipodal, finding strong evidence that they are not. This is not too surprising, as only rather special reversals would lead to antipodality. They use these poles to simulate the VGP reversal paths which would be recorded when one VGP pole is gradually replaced over time by the VGP pole of the opposite polarity, attempting to mimic the acquisition of sedimentary remanence over an interval that is long compared with the reversal duration (Fig. 2).

Actually, the analysis is more subtle than Fig. 2 suggests. In addition to measuring near-transitional pairs of VGPs, the authors measure VGPs and simulate transitions from stable field states well away from the reversal. The results are rather impressive, at least for their particular rocks: nearly all the reversal data correlate well with the synthetic data formed by averaging the near-transitional poles, although occasionally they appear to follow the stable-field versions. The implication is, then, that sedimentary records tell us more about the pre- and post-transitional VGPs than about the actual reversal — it also helps to explain how we can observe different (for example, antipodal) VGP paths for a single reversal, because, depending on the sedimentary recording mechanism, we can record the VGP path from either of two pairs (stable or near-transitional) of poles.

Constable's analysis concentrates on the record of stable polarity direction measurements recorded in lavas over the past 5 Myr, using the dataset compiled by Lee[9]. Some of these data have been available since the early 1960s, and they were shown to give VGPs which were both 'far sided' (beyond the geographical pole with respect to the observation site) and 'right handed' (having positive declinations)[10,11]. However, previous analyses generally concluded that the data gave VGPs which were equally scattered in longitude around the geographical North Pole. The remarkable picture from Constable's analysis is that, contrary to popular belief, the individual VGPs (over 2,000 of them) are actually biased towards two longitudes, and these are the same longitudes seen predominantly in the reversal records. This conclusion seems to be insensitive to both the distribution of sampling sites and also to the effects of recent plate motions. Constable also notes that the present-day VGPs cluster in one of these preferred bands, and a reversal now would track through the Americas.

Where does this leave us? Both analyses lead to the conclusion that the magnetic field has preferred orientations in space. The obvious candidate for directional control is the mantle, because convection in the mantle occurs on a timescale that is long compared to that for convection in the core. Given perfect spherical geometry, the convective motions in the core responsible for field generation would tend to drift around the rotation axis, and it has been conjectured that anomalies in temperature or heat flux at the core–mantle boundary could prevent this drift[12]. Seismic velocity anomalies at the base of the lower mantle certainly provide evidence for inhomogeneities, which could be interpreted in terms of temperature differences. This conjecture has now been put on a firm mathematical footing, for convection without magnetic fields at least. Zhang and Gubbins[13] find that drifting convection rolls can indeed become locked into anomalies in temperature on the boundaries for long periods of time, provided the phase of convection and of the boundary anomalies is correct. Clearly a firming-up of recent ideas, as well as some old ones, is happening. □

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FULLERENES

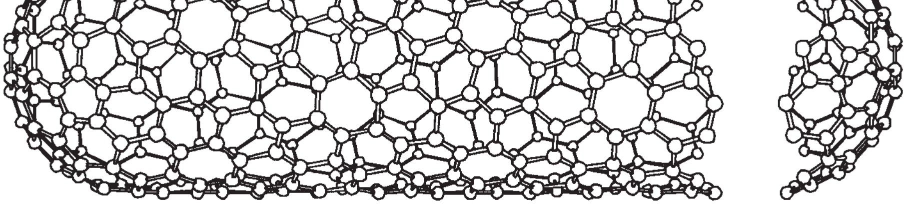
Down the straight and narrow

M. S. Dresselhaus

JUST as the discovery by Krätschmer *et al.*[1] of a method to synthesize fullerenes in gram quantities heralded a flood of activity in the study of C_{60}, the report of the large-scale synthesis of carbon nanotubes by Ebbesen and Ajayan, on page 220 of this issue[2], should stimulate a flurry of experimental work on these tubular relatives of the fullerenes. In particular, the availability of macroscopic quantities of carbon nanotubes should make it possible for experimentalists to test the exotic electronic and mechanical properties recently predicted for them.

In their report, Ebbesen and Ajayan describe the production of copious quantities of carbon nanotubes embedded in a geode-like cylindrical shell. Their method appears in many ways similar to that used by Bacon in 1960 to grow graphite whiskers[3]. Both used a d.c. discharge between carbon electrodes (75–80 volts and 70–76 amps for Bacon compared with 18 volts and 100 amps for Ebbesen and Ajayan), the positive electrode having a smaller diameter than the negative electrode, and both carried out the discharge in an inert gas (at the high pressure of 92 atmospheres for Bacon, whereas the new work uses a modest pressure of 2/3 atmosphere). When Bacon cracked open his hard cylindrical boules, he found, protruding from the fracture surfaces, scroll-like carbon whiskers up to 3 cm long and 1–5 μm in diameter. These revealed great crystalline perfection, and had high electrical conductivity and elastic modulus. Since their discovery, graphite whiskers have been the standard by which the performance of carbon fibres is measured.

In the area of nanotubes, the present standards for comparison have been theoretical models. Calculations have been done, in our laboratory and in many others, on graphene nanotubes[4–6], consisting of a planar honeycomb network of carbon atoms on a graphite sheet one atom thick and rolled up into a



Theoretical model of a single-layered carbon nanotube showing caps at each end and the tube's chirality.

cylinder. These nanotubes have remarkable properties when the diameter of the cylinder is comparable to that of the C_{60} molecule and the length is much greater. Each nanotube is specified by its diameter and the chirality of the atomic rows of carbon atoms relative to the cylinder axis (see figure showing atomic arrangement and chirality for a graphene nanotube). The 2π periodicity of the cylinder restricts the number of allowed electron wave vectors in the circumferential direction, the allowed number depending on the fibre diameter and chirality.

Calculations show that approximately a third of the possible tubes with diameters comparable to those of typical fullerenes are metallic[4-6], as is also the case at room temperature for a planar graphite sheet one atomic layer in thickness. However, for the remaining two-thirds of the possible thin nanotubes, an electronic band gap forms. Thus theory predicts that whether a graphene nanotube is metallic or not is determined by geometric considerations.

Such a situation is exceptional in solid-state physics. The availability of carbon nanotubes should allow the prediction to be tested by, for example, scanning-tunnelling-microscope (STM) spectroscopy for a single-layer tube, whose diameter and chirality might also be measured with the same microscope. More detailed tests of these theories could be provided by varying the voltage of the STM tip relative to that of the tube, thereby providing information on the density of states near the electrons' characteristic Fermi energy for various fibre geometries.

Strength

Calculations of the mechanical properties[7] suggest that carbon nanotubes are significantly stiffer than currently available carbon fibres or, in fact, than any presently known material. Furthermore, the strong sp^2 bonding and very small C–C distance would appear to inhibit the introduction of impurities and defects into the nanotubes, thereby offering the potential of great tensile strength. Experimental confirmation of these predictions would be significant in establishing the ultimate performance limits for carbon fibres[8], a technologically important commercial material in the space age.

While calculations have focused on single-layer graphene tubes with diameters comparable to that of C_{60}, experimental observations[2,9,10] have mainly involved specimens comprising two or more concentric tubes, and with diameters of more than 20 Å. Because the semiconducting gap between the electronic valence and conduction bands decreases approximately as the inverse of the fibre diameter, experimental work will probably be mostly on tubes with the smallest available diameters, where the geometric effects are predicted to be largest and the most interesting behaviour is expected. Calculations done in our group on bilayered tubes provide some justification for relating the concentric tubes that are now experimentally available to the electronic properties predicted for single-layer tubes: interactions between concentric adjacent tubes do not apparently destroy the metallic or semiconducting properties of the constituent layers.

Growth

The availability of copious amounts of carbon nanotubes will not only help in the exploration of their exotic electronic structure and mechanical properties, but should also stimulate study of the way they grow. In essence, the growth of fullerene balls and tubes involves the addition of a sequence of individual carbon hexagons. If, as claimed (M. Endo and H. Kroto, personal communication), the accretion of carbon atoms onto a tube is catalysed at a pentagonal face in the tube's end cap (see figure), then the growth mechanism should also be related to the growth mechanism for general fullerenes. STM studies of carbon nanotubes in the cap region or near an open end (if such exists) may be a good way to elucidate fullerene formation and growth.

Lastly, it is intriguing to think that nanoscopic electronic devices could be worked up from concentric semiconducting and metallic carbon tubes. These could function as capacitors in memory devices or as transistors in switching circuitry. Because the tubes do not require any doping by impurities, as conventional semiconductors do, but gain their electronic properties from their geometry, the resulting devices should be highly thermally stable and have high intrinsic mobility. □

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DAEDALUS

Space mothballs

BIG orbiting mirrors to focus sunlight down to the ground have often been suggested. Daedalus now proposes a novel orbiting lens.

His first idea was a transparent space balloon, inflated to low pressure with some refractive gas. A spherical balloon lens would be easier to make than a conventional lenticular one, and would not have to be oriented to face the Sun; but spherical lenses have dreadful optical aberrations. The Luneberg spherical lens gets round this problem. It is cunningly made of concentric layers, whose refractive indices drop off from the centre to the outside.

The obvious way to implement a Luneberg gas lens in space is to introduce gas steadily in the middle, and let it flow and expand in all directions out into the surrounding vacuum. The refractive index will then drop off radially, with the density of the outflowing gas. Even better, the outer envelope is then unnecessary. The lens becomes an enormous tenuous gas cloud spreading continuously from a tiny evaporating nucleus — which need only be a block of some volatile solid like naphthalene.

So Daedalus's proposed space lens is simply a large naphthalene mothball. Once in orbit, it will develop a huge Luneberg-lens atmosphere of expanding naphthalene vapour, hundreds of kilometres across, intercepting gigawatts of sunlight but deviating it very weakly. The lens will have a focal length of hundreds or thousands of kilometres, comparable with its orbital height. It will focus a solar hotspot on the Earth beneath.

No feasible orbit could hold this hotspot geostationary. Daedalus plans an oblique orbit to write a 'raster' on the rotating Earth beneath: not a narrow trail of fire and destruction, but a wider, less focused band. Each pass of the mothball would bring a fiercely bright five minute heatwave, with equivalent brief twilit cold snaps on either side from where the sunlight has been deviated.

A set of orbiting mothballs, each replaced when it has nearly evaporated, will bring these sunlight pulses regularly to most points on Earth. Plant life everywhere will benefit; for photosynthesis is more efficient in interrupted light. Global weather will also improve. At each pass of each mothball, the cold phases will trigger thick clouds into raining, while the hot phase will burn off thin cloud. Countries which now only have climate will enjoy real weather! Solar energy could be locally captured too. Thermal collectors, timed to open briefly as each mothball passed overhead, could accumulate free heat for hot water, and free cold for air conditioning. David Jones