Phys Educ, Vol 13, 1978 Printed in Great Britain

Brownian motion—June 1827

J G POWLES
Physics Laboratory, University of Kent at Canterbury

Robert Brown

'I have some sea-mice—fine specimens—in spirits. And I will throw in Robert Brown's new thing—*Microscopic Observations on the Pollen of Plants*—if you don't happen to have it already'.
George Eliot, *Middlemarch* (1872)

1977 saw the sesquicentenary of the observation and discovery by Robert Brown (1828) of a fundamental scientific phenomenon which we now call Brownian motion. Robert Brown was an eminent botanist. His biographies (Stearn 1962, 1970, *Encyclopaedia Britannica* 1910) relate at length his botanical work but give less prominence to Brownian motion, although, for physical scientists at least, this was his most important and enduring contribution to science.

Robert Brown (1773-1858) was born in Montrose, Scotland. He studied medicine in the universities of Aberdeen and Edinburgh but appears not to have formally completed his course, possibly because while in Edinburgh he acquired a consuming interest in botany. Nevertheless he served in the British army in the north of Ireland (times do not change much!) as an assistant surgeon! In 1801-5 he was sent by Sir Joseph Banks as botanist on a voyage to New Holland (Australia) to collect and classify new plants. However, he was more than a classifier. He was interested in plant physiology and this led him to a study of the behaviour of pollens suspended in water. In June-August 1827 he examined pollen grains of *Clarkia pulchella*, which have a diameter of some 0.3-1 μm, in water under a microscope, which seems to have been one of the best available at that time. He reported as follows (Brown 1866 p466, Crosland 1971, my insertions in square brackets):

'... the grains of pollen were particles ... of a figure between cylindrical and oblong, perhaps slightly flattened ... While examining the form of these particles immersed in water, I observed many of them very evidently in motion; their motion consisting not only of a change in place in the fluid manifested by alterations in their relative positions [translational Brownian motion] ... In a few instances the particle was seen to turn on its longer axis [reorientational Brownian motion]. These motions were such as to satisfy me, after frequently repeated observations, that they arose neither from currents in the fluid, nor from its gradual evaporation [convection], but belonged to the particle itself'.

As the botanist W T Stearn (1970) says:

'He thereupon extended his observations to numerous species belonging to many families of plants and found such motion in the particles of all fresh pollen. This led him to enquire whether the property continued after the death of the pollen [the precise difference in the motion of living and dead 'particles' has only recently been properly elucidated by experiments on scattering of light by bacteria (Berge *et al* 1967, Nossal *et al* 1971)]. Ultimately, after examining powdered pit coal and glass, numerous rocks†, and metals in a finely divided state, Brown (1828) stated that such active particles occurred in every mineral he could reduce to a powder sufficiently fine to be suspended in water ... to Brown belongs the

---

† Including, it is claimed (MacDonald 1962 p8), even powdered sphinx, which is no doubt active in the sense of being aphrodisiac.

0031-9120/78/0005-0310 $01.00 © 1978 The Institute of Physics

credit for establishing such motion as a property not simply of living pollen but of all minute particles, inorganic as well as organic, suspended in a fluid'.

Robert Brown is sometimes thought to have believed that the particles had to be alive but he refutes this rather charmingly (Brown 1866 p480):

> 'In the first place, I have to notice an erroneous assertion of more than one writer, namely that I have stated the active molecules [i.e. particles] to be animated. This mistake has probably arisen from my having communicated the facts in the same order in which they occurred accompanied by the views which presented themselves in the different stages of the investigation . . .' [a mistake which no one writing a scientific paper today would make—more's the pity].

Brown's experiment can easily be performed with a moderately powered microscope in a school laboratory and is used in the first-year physics laboratory as a method of determining Avogadro's number (see below). Nevertheless the proper analysis of the phenomenon in a quantitative way had to wait almost eighty years until Einstein (1905). There is no doubt that Brown recognised his motion as a fundamental phenomenon. However he offered no explanation and did nothing quantitative, but he did carry out observations under controlled conditions and performed an experiment which eliminated many other possible causes, principally motion due to convection currents. Many who followed him were less careful and heated controversy ensued.

It has been claimed (Truesdell 1975) that Brown was anticipated by Lucretius in *c*60 BC (Munro 1886):

> 'Observe whenever the rays . . . pour the sunlight through the dark chambers of houses: you will see many minute bodies . . . in the midst of the light of the rays, which, as in never-ending conflict, skirmish and give battle . . . Such tremblings imply that motions also of matter latent and unseen are at the bottom . . . Thus motion mounts up . . . to our senses so that those bodies also move, which we can discern in the sunlight, though it is not clearly seen by what blows they so act'.

This explanation is astonishingly in accord with our present view that Brownian motion is due to the multiple impact of molecules of the solvent (air here) on the larger particles which are being observed. However, there is little doubt that the actual motion observed by Lucretius was macroscopic and due mainly to convection and turbulence.

It is of interest from the point of view of scientific method that the proper quantitative analysis of Brownian motion was not found for so long because the many able experimentalists following him were observing the wrong quantity. It was natural to observe the *velocity* of the particles but what one observed with the eye is not what the particle is actually doing owing to the limitations of the frequency response of the human optical system and is a rather subtle matter (MacDonald 1962 p11) (see note). Only when this is allowed for does one find from visual observations of Brownian motion that the root mean square velocity in one direction is as predicted by kinetic theory $[(kT/m)^{1/2}]$. Einstein's vital contribution was to direct attention to the *distance* the particle moved—or, more precisely, the mean square distance, $\overline{x^2}$. According to Einstein this should be proportional to the time of observation t, i.e. $\overline{x^2} = 2Dt$, and Einstein, in a *tour de force* and in language unfamiliar to us today, obtained a fundamental expression for the coefficient of self-diffusion, D, of the Brownian particle in the solvent. This led directly to Perrin's (1916) determination of Avogadro's number, a quantity of immense fundamental importance since it in effect gives the size of an atom.

Note

The velocity of the Brownian particle varies with time and so may be represented by $v(t)$. For such 'stationary random variables' it is useful to consider the correlation of the value at time t with the value at a time τ later, on the average, i.e. averaged over t, which we write $\langle v(t)\, v(t+\tau)\rangle_t$ and which is clearly a function of τ only. This quantity falls appreciably towards zero for a characteristic time τ_v which is the time for which the velocity is correlated. If we Fourier analysed $v(t)$ we would find (Wiener-Khinchine theorem) that the power spectrum of $v(t)$ contains frequencies uniformly up to about an angular frequency of $1/\tau_v$ and virtually none above. Thus the frequency spectrum of v^2 is smeared over a range of frequencies from zero to $1/\tau_v$. The correlation time τ_v for the velocity of the Brownian particle of mass m and radius a is in fact $m/(6\pi\eta a)$ where η is the viscosity of the solvent. If the response time of the eye is τ_e it does not observe frequency components higher than $1/\tau_e$, consequently since $\tau_e >> \tau_v$ one only observes the fraction (τ_v/τ_e) of the true mean square velocity, or $(\tau_v/\tau_e)^{1/2}$ of the root mean square velocity, and this fraction is about 10^{-3}.

The corresponding effect for electrons in a conductor, or indeed charge carriers in any material, is the Johnson 'noise' voltage which sets the limit to the accuracy of virtually all measurements.

The direct descendant of Brownian motion is the fluctuation-dissipation approach (e.g. $\overline{x^2}$ is a fluctuation and η a dissipation—see note) which today dominates the whole of statistical mechanics in its treatment of the thermal motion of the constituent particles of virtually all matter—including stars and nuclei.

The phenomenon of reorientational thermal motion, which is this author's particular interest (for molecules in fluids and solids), was also, as we have noted, observed by Robert Brown. It was first put on a quantitative basis for molecules by Debye as late as 1913 (Debye 1913, 1945).

Finally we must congratulate George Eliot on her topical mention of Robert Brown, which was well researched since although *Middlemarch* was first published in 1872 the story is set in 1832. Would that present-day literature referred to important scientific discoveries, which affect all our lives, in so apt a manner.

Acknowledgment

I am indebted to Professor J T Lewis of the Dublin Institute for Advanced Studies for drawing my attention to the literary reference to Robert Brown given at the beginning of the article.

REFERENCES

Berge P *et al* 1967 *C. R. Acad. Sci., Paris* D **265** 889

Brown R 1828 *A Brief Account of Microscopical Investigations ... on the Particles Contained in the Pollen of Plants* privately circulated in 1828

——1866 *Miscellaneous Botanical Works* vol. 1 (London: Royal Society)

Crosland M P (ed) 1971 *The Science of Matter* (Harmondsworth: Penguin) p235

Debye P 1913 *Ber. Bunsenges. Phys. Chem.* **15** 777

——1945 *Polar Molecules* (New York: Dover)

Einstein A 1905 *Ann. Phys., Lpz* **17** 549

——1906 *Ann. Phys., Lpz* **19** 289, 371

Encyclopaedia Britannica 1910 11th edn, vol. IV (Encyclopaedia Britannica: New York) p661

MacDonald D K C 1962 *Noise and Fluctuations* (Chichester: Wiley)

Munro H A J (trans) 1886 *Lucretius De Rerum Natura II* (Cambridge: Deighton Bell) pp114-41

Nossal R *et al* 1971 *Opt. Commun.* **4** 35

Perrin J 1916 *Atoms* (Wokingham: van Nostrand) p115

Stearn W T 1962 *Three Prefaces on Linnaeus and Robert Brown* (Weinheim: Cramer)

——1970 *Dictionary of Scientific Biography* vol. II (New York: Scribner)

Truesdell C (ed) 1975 'Early kinetic theories of gases' *Arch. Hist. Exact Sci.* **15**

Inter Navex

Inter Navex 78 will consist of a two-day conference on alternative learning systems (16-17 October) and an exhibition of audio-visual products (16-18 October). It will be held at the Wembley conference centre, and further details can be obtained from the Organiser, Inter Navex 78, NCAVAE, 254 Belsize Road, London NW6 4BY (tel. 01-624 8812).

ALTERNATIVE ENERGY SOURCES

An appraisal of the tides as an alternative energy source

T L SHAW
Department of Civil Engineering,
University of Bristol

There is a continuing need to plan for the provision of future energy supplies. This is seldom a straightforward process and it can be very difficult and contentious. The options and pitfalls have never been more challenging and vital for correct solution than at the present time. Many factors are involved and these are generally known. The basic criteria for an acceptable energy supply, namely to be available on demand at minimum overall cost, must remain our guide. But when demands *and* costs are particularly uncertain, an essential ingredient of planning must be the flexibility to adjust to rapidly changing circumstances. Is this possible, and if so how can it be achieved and with what sacrifices?

These are fundamental questions that must affect future demand for all energy sources. Those chosen must be mutually compatible in order to meet the 'efficiency' specification defined above. For example, consider the provision of electricity (this form of energy provides about one-third of the total used in the UK). It is tempting to think that the cheapest supply comes from the cheapest source, and hence mass production by that means alone is the answer. While this may be true in principal, consider the following, equally indisputable facts:

(1) The lowest unit electrical costs are achieved by large stations.

(2) It requires a minimum of ten years, and in many cases more than 15 years, to plan, construct and commission large stations.

(3) The life of thermal stations (coal, oil, gas, nuclear) is typically about 30 years.

(4) Developments in technology have led to changes in the most economic fuel source. Coal held prime place for many decades, followed by oil for about 25 years; now there is a case for nuclear. Will there be another change in the short time span to 2020, i.e. before nuclear stations planned now are 30 years old?

(5) To favour investment in one source at any time

0031-9120/78/0005-0312 $01.00 © 1978 The Institute of Physics