and collected some more plants. Finally, leaving there on August 18, Douglas arrived at the settlement of York Factory on the eastern end of Hudson Bay on July 28, 1827, concluding his journal with:

I sailed from Hudson's Bay on September 15th and arrived at Portmouth on October 11th, having enjoyed a most gratifying trip.

D. Brown

As shall be seen, pollen from *Clarkia pulchella* flowers, grown from the seeds shipped out by Douglas, were put to use by Robert Brown as soon as possible. Biographies of Robert Brown (1773-1858), a comprehensive book[12] as well as short and web-accessible sketches[13][14][16] are available, so only a brief outline shall be given here. Already in his teenage years, Brown had a strong interest in botany. While attending medical school at the University of Edinburgh, he collected plants in Scotland, and befriended people of like interest. He left the university in 1793 without his medical degree and joined the Army in 1794. He was sent in 1795 to serve in Ireland as a surgeon's mate. He spent as much of his time there as he could spare doing botany. He visited London in the summers of 1798 and 1799, networking with other botanists.

At the time, Joseph Banks (1743-1820) was the most influential botanist in England. His initial fame was gained from plant collecting during Captain Cook's first expedition (1768-1771). Banks was president of the Royal Society from 1778 until his death. (He appears as a colleague of Stephen Maturin in the novels of Patrick O'Brian!). He convinced the Admiralty of the desirability of charting the coast of Australia and collecting plants there. Having heard good things about Brown, Banks wrote him a letter on December 12, 1800, offering the post of naturalist on the expedition. Brown accepted with alacrity. He obtained leave from his military duties, traveled to London, and became acquainted with Banks. Brown also met Ferdinand Bauer (1760-1826), a superb botanical illustrator, who was to accompany him on the trip. Brown prepared diligently. The ship *Investigator* set sail for Australia on July 18, 1801. Brown had many adventures as an indefatigable collector of plants (but also of animals, birds, fishes, reptiles, insects and rocks). He returned on October 7, 1805, having found thousands of new species of plants.

Brown's work had been so impressive that, before the year ended, he was chosen to be librarian of the Linnean Society. With salary and free lodgings in prospect, he quit the army. Also, Banks convinced the Admiralty to continue Brown's salary, and that of Bauer, as they codified their work. In the next five years, Brown wrote ground-breaking papers on plant classification, often aided by microscopic observations. In 1810 he published Volume 1 describing his Australian plants. The projected Volume 2 was never published, because the first volume was a financial failure, but much of the remaining material later emerged in various papers. In that year, Banks hired him as the librarian and curator of Banks's herbarium. Together with his arrangement with the Linnean Society, this made him financially secure (the Admiralty stipend ended the following year).

Brown was extremely active professionally, at the hub of botanical research in England, and was increasingly admired throughout Europe, not least because of his remarkably perceptive microscopy. A forte was characterizing plants by the nature of their reproductive organs and seeds, a scheme that was superior to the Linnean system then prevalent.

Banks died in the middle of 1820. He left his library, herbarium, an annuity and eventually the lease to his house to Brown, with the stipulation that Brown take up residence there. The botanical materials were to go eventually to the British Museum, subject to Brown's convenience. He leased half of the house to the Linnean society for their collections and use, and soon resigned from his paid Linnean positions. In 1825 he declined an offer of the Linnean Society, writing that one who occupied the proffered position of Secretary ... *should unquestionably have the habits of a man of business and be perfectly regular in matters of correspondence. That I do not possess such habits at present is but too well known to all my friends and whether I should ever acquire them is at least very doubtful.*

Nonetheless, despite his protestation of lack of business acumen, his negotiations with the Trustees of the British Museum for the transfer of Banks's library, which took more than a year, concluded in September 1827 with satisfying success. He was to become the underlibrarian in charge of the collection. There was a good stipend for two days work a week and a full-time paid assistant John Joseph Bennett (1801-1876) who became a friend and eventually Brown's executor. The terms were such that he retained his rooms, stipend from Banks and control of Banks's herbarium. During these negotiations, Brown was conducting the investigations of concern here.

III. JIGGLY

When the seeds Douglas had shipped out arrived at the Horticultural Society in early spring 1826, they came under the purview of John Lindley (1799-1865)[17]. Lindley had been mentored by Brown: in 1818, Brown gave Lindley a job that lasted a year and a half working in Banks's herbarium[12]. In 1821, the Horticultural Society leased 33 acres in Chiswick for an experimental garden[18]. The next year, Sabine hired Lindley to be assistant secretary of the garden, to superintend the collection of plants and their propagation.

The Natural History Museum in London (which spun off from the British Museum in 1881) has an extensive collection of Brown's papers. In box 24 of Brown's "Slips Catalogue," sheet #224 is labeled Clarkia[19]. Directly underneath, Brown's (not always legible) handwriting reads *Hort Soc* (Horticultural Society) *Horticult (illegible) Chiswick (illegible)*, and the next line reads *occident* (western) *Amer (illegible) by D Douglas*. Thus, Brown certifies that his *Clarkia pulchella* flowers came directly from the Horticultural Society's garden. Flowers or seeds could be distributed to Fellows of the Society, but Brown was not one. Therefore, he likely received *Clarkia* flowers privately from John Lindley[20].

Sheet #224 contains entries dated June 12, 1827 and June 13, 1827. The first entry begins by describing the pollen[21]:

> *The grains of Pollen are subspherical or orbiculate-lenticular* (circular-lens shaped) *with three equidistant more pellucid and slightly projecting points so that they are obtusely triangular. ...*

Figure 1 shows the pollen viewed under a microscope. Figure 2 is an electron microscope picture of the pollen. It looks vaguely like a pinched tetrahedron with the longest dimension around 100 microns[22] and "pores" at three vertices.

FIG. 1: *Clarkia pulchella* pollen imaged by a microscope at x400.

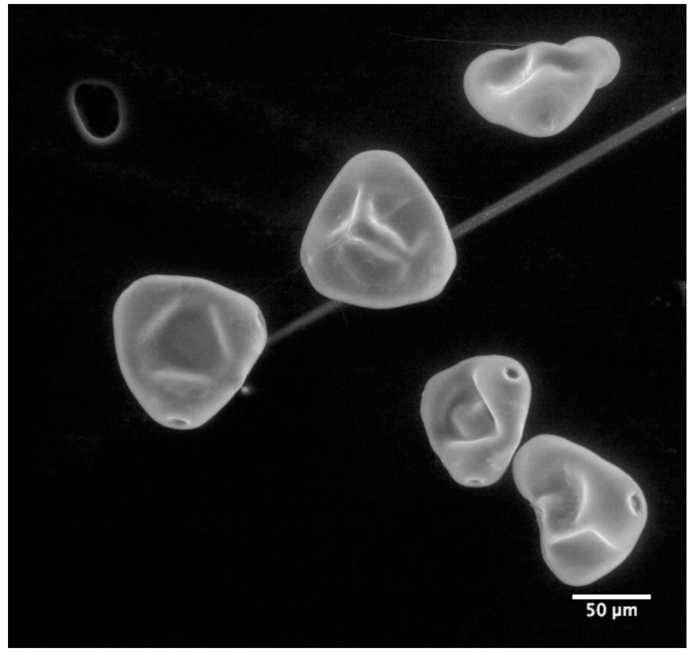

FIG. 2: *Clarkia pulchella* imaged by an electron microscope.

The entry turns to the contents of the pollen:

> *The fovilla or granules fill the whole orbicular disk but do not extend to the projecting angles. They are not spherical but oblong or nearly cylindrical. & the particles have a manifest motion. This motion is only visible to my lens which magnifies 370 times. The motion is obscure but yet certain. ...*

Thus began the research that resulted in Brown's wonderfully discursive paper[23], dated July 30, 1828, and entitled:

> *A brief Account of Microscopical Observations made in the Months of June, July and August 1827, on the Particles contained in the Pollen of Plants; and on the general Existence of active Molecules in Organic and Inorganic Bodies.*

It was first privately published as a pamphlet, treated as a preprint and given to various colleagues. However, it was published in September.

This is a superb example of a researcher of unusual capability and energy delineating his thought processes. Some of its 53 paragraphs shall be treated here in some detail, especially the first nine that describe Brown's interaction with *Clarkia* and the start of a broader investigation.

A. Brown's Microscopes

The paper begins with a description of his microscope in the first paragraph:

> *The observations, of which it is my object to give a summary in the following pages, have all been made with a simple microscope, and indeed with one and the same lens, the focal length of which is about 1/32 of an inch.*

Brown expands in a footnote:

> *This double convex Lens, which has been several years in my possession, I obtained from Mr. Bancks, optician, in the Strand. After I had made considerable progress in the inquiry, I explained the nature of my subject to Mr. Dollond, who obligingly made for me a simple pocket microscope, having very delicate adjustment, and furnished*

with excellent lenses, two of which are of much higher power than than that above mentioned. ...

However, he added that he only used the Dollond microscope *... in investigating several minute points.*

A well known rule of thumb is that a near object is best seen at a distance of 10 inches. This puts the magnification Brown used at $\approx 10/f = 320$, which is not far from Brown's own estimate of $\times 370$ cited above.

The whereabouts of this lens is not known. There does exist a pocket microscope of Brown's made by Bancks, in a box of dimensions less than 1"x2"x5". Upon Brown's death, Bennett gave this microscope *... which he was in the daily habit of using at the museum ...*[24] to a mutual friend, and it has ended up at the Linnean Society. It has a complete set of lenses, the strongest of which has magnification $\times 170$. Bennett gifted another Bancks microscope, used by Brown at home, whose strongest lens has magnification $\times 160$: this is now in the museum at Kew Gardens. These are all the extant microscopes that can definitively be traced to Brown. There is also a pocket microscope at the University Museum of Utrecht, made by Dollond, with highest power lenses $\times 330$ and $\times 480$ magnification that associated documents suggest bears a relationship to Brown's Dollond microscope[24].

The Linnean Society microscope's $\times 170$ lens has been conjectured by Ford to be the one Brown used for his Brownian motion observations[24][25], and the microscope at Utrecht is thought to be essentially identical to Brown's microscope made by Dollond. Ford proposed that Brown meant the working distance of the lens (the distance between the front of the lens and the viewed object) when he stated that the focal length was 1/32 inch. Ford also surmised that the above-mentioned extant microscopes represent Brown's full collection. If so, since the $\times 170$ lens is the strongest Bancks lens extant, it is the best candidate. In addition, Brownian motion can be observed with it[14], albeit of milk fat globules[15]. Indeed, as Brown asserted in his footnote, the $\times 170$ lens is much less powerful than the Utrecht $\times 330$ and $\times 480$ Dollond lenses.

However, these conjectures are doubtful.

The $\times 170$ lens (which therefore has a focal length of 1/17 inch) was measured by Ford to have a working distance of 1.5mm=1/17inch, not 1/32inch[25]. [Regardless, there must be some mistake. Half the lens thickness is the difference between the working distance and the focal length of the lens (which is essentially the object distance, for a magnifying glass). If both these numbers are 1/17 inch, this implies that half the lens thickness is 0!]

Moreover, Brown had many microscopes. Upon his death, the *Gardener's Chronicle* magazine reported that at least 9 microscopes of his were sold, some made by Bancks[36].

Brown likely had two Dollond lenses of power much larger than $\times 370$, as he said in his footnote. The French botanist Alphonse de Candolle (1806-1893) visited Brown in 1828. He wrote to his famous botanist father that Brown had showed him the motion of granules from pollen, and added[27]:

For that he only works with the simple lenses. But it is true that the lenses of English manufacture are as strong as many compound microscopes, because they magnify up to 800 and 1000 times. Mr. Brown has had 30 or 40 made by Dollond and other famous opticians and he chooses from them 5 or 6 in number, with which he usually works. He obtains thus the effect of an ordinary microscope with the clarity and the reliability of a simple lens.

This is supported in a remark contained in an addendum by Brown entitled *Additional Remarks on Active Molecules* written a year later[23]. Brown says that the new work described there

... employed the simple microscope mentioned in the Pamphlet as having been made for me by Mr. Dollond, and of which the three lenses that I have generally used, are of a 40th, 60th and 70th of an inch focus.

Thus, he says he has lenses of power $\times 600$ and $\times 700$, which agrees with his footnoted remark, *two of which are of much higher power* than the $\times 370$ lens.

Brown was the most astute microscopist of his day, and known to be extremely cautious with his statements. We believe he should be taken at his word: he used a $\times 370$ lens.

These are remarkably small lenses, with surface radii, thickness and diameter comparable in size to the focal length. Such lenses are like those of Leeuwenhoek (1632-1723)—a delightful recent paper describes grinding such a lens[28].

Brown apparently preferred simple microscopes rather than compound microscopes. Charles Darwin (1809-1882) visited Brown in 1831, just before the voyage of the Beagle, to consult about what microscope to take. He wrote in his "Life and Letters," *I saw a good deal of Robert Brown ... He seemed to me to be chiefly remarkable for the minuteness of his observations and their perfect accuracy. ....* He was advised to take a Bancks single lens microscope on the voyage, which he did. This microscope is at Darwin's home, Down House in Kent.

The way to construct a compound microscope that was superior to a single lens was not well known at the time, because of spherical aberration. Joseph Jackson Lister (1786-1869) (father of the surgeon Joseph Lister who instigated antiseptic operations, after whom the mouthwash Listerine was named) discovered how to minimize spherical aberration in compound microscopes, by appropriately separating lens elements. He commissioned construction of such a microscope in 1826, but only published the concept in 1830[29].

As is discussed in detail later in this paper, a single lens, with appropriate choice of the exit pupil, can have negligible spherical aberration. In addition, a single lens microscope is more portable. Darwin only replaced his Beagle microscope, which served the dual purpose of observation and dissection, by two microscopes, a compound microscope in 1847 and a dissecting microscope of his own design in 1848. Concerning the latter, he wrote to a friend: *... I have derived such infinitely great advantage from my new simple microscope, in comparison with the one which I used on the Beagle ... . I really feel quite a personal gratitude to this form of microscope & quite a hatred to my old one.*[30]

B. Observing *Clarkia pulchella*

The second paragraph mentions a paper Brown had published in 1826, which

... led me to attend more minutely than I had before done to the structure of the Pollen, and to inquire into its mode of action on the Pistillum ...

The pistil, the female part of a flower, consists of a vase-like object called the style, containing at its bottom the ovules (immature seeds containing eggs) and a structure on top called the stigma. Others conjectured that, when a pollen grain sticks to the stigma, the grain releases the particles it contains, and these somehow travel down through the style to fertilize the ovules. In his third paragraph, Brown expresses doubts *respecting the mode of action of the pollen in the process of impregnation.*

As explained in the fourth and fifth paragraphs, he had the idea to look into this too late in the year, past the time of flowering:

It was not until late in the autumn of 1826 that I could attend to this subject; and the season was too far advanced to enable me to pursue the investigation. Finding, however, in one of the few plants then examined, the figure of the particles contained in the grain of pollen clearly discernible, and that figure not spherical but oblong, I expected with some confidence to meet with plants in other respects more favorable to the inquiry, in which these particles, from peculiarity of form, might be traced through their whole course ... .

I commenced my study in June 1827, and the first plant examined proved in some respects remarkably well adapted to the object in view.

Thus Brown explains his selection: among a number of flowers apparently chosen by chance, *Clarkia pulchella* pollen clearly contained oblong particles.

For what follows, note that the male part of a flower, the stamen, consists of two parts. There is the anther, which is a sack in which pollen grains develop; it sits on a stalk called the filament, which conveys nutrients from the flower to the anther. When the pollen is ripe, it is released because the anther bursts, splitting longitudinally (in most cases), a process called *dehiscence.*

The sixth paragraphs launches the investigation.

This plant was Clarckia pulchella*, of which the grains of pollen, taken from antherae fully grown before bursting, were filled with particles or granules of unusually large size, varying from 1/4000th to about 1/3000th of an inch in length, and of a figure between cylindrical and oblong, ... While examining the form of these particles immersed in water, I observed many of them very evidently in motion ... . In a few instances the particle was seen to turn on its longer axis. These motions were such as to satisfy me, after frequently repeated observation, that they arose neither from currents in the fluid, nor from its gradual evaporation, but belonged to the particle itself.*

This is the first kind of particle Brown observes, whose length he estimates at about 6 to 8 microns. This is worth noting, since observations discussed later in this paper give these particles shorter lengths. The difference shall be attributed to the alteration of the image by his lens, as mentioned earlier.

In the seventh and eighth paragraphs, he notes the existence of a second kind of particle;

Grains of pollen of the same plant taken from antherae immediately after bursting, contained similar subcylindrical particles, in reduced numbers however, and mixed with other particles, at least as numerous, of much smaller size, apparently spherical, and in rapid oscillatory motion.

These smaller particles, or Molecules as I shall term them, when first seen, I considered to be some of the cylindrical particles swimming vertically in the fluid. But frequent and careful examination lessened my confidence in this supposition; and on continuing to observe them until the water had entirely evaporated, both the cylindrical particles and spherical molecules were found on the stage of my microscope.

C. Seeing Brownian Motion

We emphasize here that Brown was *not* observing the pollen move. He was observing much smaller objects, which reside within the pollen, move. This is well known—see for example the excellent pedagogical article by Layton[31]. Nonetheless, statements that Brown saw the pollen move are rife[32].

A *Clarkia* pollen is $\approx 100\ \mu m$ across[22]. As we shall shortly show, that is too large for its Brownian motion to be readily seen. However, fortunately for Brown, the contents of the pollen are just the right size for their motion to be conveniently observed.

To understand this, one may employ Einstein's famous equation for the mean square distance $\overline{x^2}$ travelled by a sphere of radius R in time t, in one dimension, in a liquid of viscosity η at temperature T, Eq. (A6) with

Eq. (B17):

$$\overline{x^2} = \frac{2kTt}{6\pi\eta R},$$

where k is Boltzmann's constant.

As shown following Eq. (A6), the mean distance travelled is $\overline{|x|} \approx .80\sqrt{\overline{x^2}}$. For an oblong object, as discussed in Appendix B, the equation is the same except that R is to be replaced by an effective radius R_{eff}. For example, for an ellipsoid of revolution whose length is $2a$, with maximum cross-section a circle of diameter a, R_{eff} lies approximately in the range $.6a - .7a$, depending upon the angle between the direction of motion and the long axis (Eqs. (B18), (B19)).

Similar results are to be expected even for a weirdly-shaped object like *Clarkia* pollen. For the pollen and its contents, one may estimate using the expression

$$\overline{|x|} \approx .80\sqrt{\frac{2kTt}{6\pi\eta R_{\text{eff}}}} \approx 5.2\times10^{-7}\sqrt{\frac{t_{\text{sec}}}{R_{\text{eff-cm}}}} \approx .52\sqrt{\frac{t_{\text{sec}}}{R_{\text{eff}-\mu m}}}\mu m, \quad (1)$$

where a micron 1 $\mu m = 10^{-3}$ mm. In Eq. (1), $T = 20°\text{C}=293°\text{K}$, and the viscosity coefficient for water at this temperature, $\eta = .01$ gm/cm-sec, were used.

TABLE I: $\overline{|x|}$ in μm for values of R_{eff} in μm and t in sec.

R_{eff}	.50	1.0	1.5	2.0	2.5	3.0	3.5	4.0	50
t=1	.74	.52	.43	.37	.33	.30	.28	.26	.07
t=30	4.1	2.9	2.3	2.0	1.8	1.6	1.5	1.4	.41
t=60	5.7	4.0	3.3	2.9	2.6	2.3	2.2	2.0	.57

Table I follows from Eq. (1). The reason for choosing $t = 1$ sec is that the little jiggles on the time scale of about a second are what catches the eye.

TABLE II: $\overline{|\theta|}$ in degrees for values of R_{eff} in μm and t in sec.

R_{eff}	.50	1.0	1.5	2.0	2.5	3.0	3.5	4.0	50
t=1	74	26	14	9	7	5	4	3	.01
t=30	402	142	78	50	36	27	22	18	.4
t=60	570	201	110	71	51	39	31	25	.6

[For later use, we have appended here a similar table for the mean angle $\overline{|\theta|}$, Eq. (A8) and Eq. (B26):

$$\overline{|\theta|} \approx .80\sqrt{\frac{2kTt}{8\pi\eta R_{\text{eff}}^3}} \approx 26\sqrt{\frac{t_{\text{sec}}}{R_{\text{eff}-\mu m}^3}}\text{degrees}, \quad (2)$$

where R_{eff} for rotation about the two ellipse axes is given by Eqs. (B27), (B28).]

It is considered that the human eye is unable to resolve angles less than 1 arcminute$\approx 2.9\times10^{-4}$ radians[33]. At a distance of 25 cm, this means a displacement less than 73 μm cannot be seen by the eye. This implies that less than a $73/370 \approx .2$ μm displacement cannot be seen by the eye with the help of a lens of magnification $\times 370$. Thus, by this rough criterion (e.g., the perception of motion may involve an altered criterion, illumination matters, and diffraction and aberration of the image has not been taken into account), from Table 1, the pollen contents with $R_{\text{eff}} < 4$ μm could be seen to move in 1 sec, but not the pollen with $R_{\text{eff}} \approx 50$ μm.

D. Observing Pollen Of Other Plants

In paragraph 9, Brown starts to look at the pollen of other plants, to see if their contents are similar and behave similarly. First, he looks at plants which have a similar classification. In the family *Oenothera* (evening primrose), *Clarkia* is a genus and *C. pulchella* is a species. Another genus in the same family is *Onagraceae*, which Brown calls *Onagrariae*:

In extending my observations to many other plants of the same natural family, namely Onagrariae*, the same general form and similar motions of particles were ascertained to exist, especially in the various species of* Oenothera*, which I examined. I found also in their grains of pollen taken from the antherae immediately after bursting, a manifest reduction in the proportion of the cylindrical or oblong particles, and a corresponding increase in that of the molecules, in a less remarkable degree, however, than in* Clarckia.

In paragraph 10, Brown remarks that this

... reduction in that of the cylindrical particles, before the grain of pollen could possibly have come in contact with the stigma, — were perplexing circumstances in this stage of the inquiry , and certainly not favorable to the supposition of the cylindrical particles acting directly upon the ovulum; an opinion which I was inclined to adopt when I first saw them in motion. ...

In paragraph 11 he is off and running, looking at a variety of flowering plants:

In all these plants particles were found, which in the different families or genera varied in form from oblong to spherical, having manifest motions similar to those already described ... In a great proportion of these plants I also remarked the reduction of the larger particles, and a corresponding increase of the molecules after the bursting of the antherae ...

Prior to discussing the next paragraph, we should emphasize that, so far, Brown had *not* observed the *particles* *or granules* moving while they were *within* the *Clarkia pulchella* pollen grain. As he says in paragraphs 6 and 8, he observed them moving in water.

Unfortunately, he doesn't say how they manage to get out of the pollen grain after the grains are put in water. As will be discussed in more detail in Section IV, pollen grains in water—in vitro—may burst open, the contents streaming out under pressure (called turgor). (What happens naturally—in vivo—will be discussed there too.) Moreover, the particles within *Clarkia pulchella* pollen seem to be too packed together to move. And, we have observed that the fluid in which they are packed is so viscous that their motion is impeded when they do emerge. However, paragraph 12 says:

In many plants, belonging to several different families, but especially to Gramineae*, the membrane of the grain of pollen is so transparent that the motion of the larger particles within the entire grain was distinctly visible; ... and in some cases even in the body of the grain in* Onagrariae.

So, Brown *was* able to see particles move within some pollen, but he does not specifically include *Clarkia pulchella*. Sometimes Brown is said to have observed particles moving within the pollen, and the implication is that this was what Brown first observed, which is incorrect[34][15].

The next two paragraphs consider plants with varied kinds of pollen but similar results. Then comes paragraph 15:

Having found motion in the particles of all the living plants which I had examined, I was led next to inquire whether this property continued after the death of the plant, and for what length of time it was retained.

Paragraph 16 reports that, from plants dried or preserved in alcohol, for a few days, to a year, to more than twenty years, to more than a century, the pollen *... still exhibited the molecules or smaller spherical particles in considerable numbers, and in evident motion, ...*

He next has the idea to look at plants that reproduce by spores: mosses and the horsetail (*Equisetum*). He finds within the moss spores, and sitting on the surface of the *Equisetum* spores, *... minute spherical particles, apparently of the same size with the molecule described in* Onagrariae*, and having equally vivid motion on immersion in water ; ... .*

E. Observing Organics

Then, as described in paragraph 19, an accident occurred. On *bruising* a spore of *Equisetum*, *... which at first happened accidentally, I so greatly increased the number of moving particles that the source of the added quantity could not be doubted.* This leads him to *bruise ... all other parts of those plants ...*, with the same motion observed.

Therefore, the motion had nothing to do with plant reproduction. He says:

... My supposed test of the male organ was therefore necessarily abandoned.

From this comes a hypothesis. The naturalist George-Louis Leclerc, Comte de Buffon (1707-1788), had proposed an atomic-style hypothesis, that there are elementary "organic molecules" (hence Brown's name for the smaller particles he observed) out of which all life is constructed. Brown signs onto this in paragraph 20:

... I now therefore expected to find these molecules in all organic bodies: and accordingly in examining the various animal and vegetable tissues, whether living or dead, they were always found to exist; and merely by bruising these substances in water, I never failed to disengage the molecules in sufficient numbers to ascertain their apparent identity in size, form, and motion, with the smaller particles of the grains of pollen.

Paragraph 21 contains this charming observation:

... I remark here also, partly as a caution to those who may hereafter engage in the same inquiry, that the dust or soot deposited on all bodies in such quantity, especially in London, is entirely composed of these molecules.

He now looks at things that were once organic, gum-resins, pit coal, then fossil wood. He then thinks of mineralized vegetable remains and looks at silicified wood, with similar results. Paragraph 22 concludes:

... But hence I inferred that these molecules were not limited to organic bodies, nor even to their products.

F. Observing Inorganics

So, (paragraphs 23-32) *... to ascertain to what extent the molecules existed in mineral bodies became the next object of inquiry. ....* Starting with *... a minute fragment of window-glass, from which when merely bruised on the stage of the microscope ...*, he tries all kinds of minerals, rocks, and metals, even *... a fragment of the Sphinx*!

... in a word, in every mineral I could reduce to a powder sufficiently fine to be temporarily suspended in water, I found these molecules more or less copiously: ...

When he looks at objects that are not spherical, such as fibers, he conjectures that they are composed of a number of molecules. He heats or burns wood, paper, cloth fiber, hair, quenches them in water and finds "molecules" in motion.

G. Brown's Summary of Observations on Molecules

Paragraphs 33-37 summarize, with commendable caution:

There are three points of great importance which I was anxious to ascertain respecting these molecules, namely, their form, whether they are of uniform size, and their absolute magnitude. I am not, however, entirely satisfied with what I have been able to determine on any of these points.

As to form, I have stated the molecule to be spherical, and this I have done with some confidence; ...

He explains that he judged the size of bodies *... by placing them on a micrometer* (a glass slide with lines ruled on it) *divided to five thousandths of an inch ... .*

The results so obtained can only be regarded as approximations, on which perhaps, for obvious reason, much reliance will not be placed. ... I am upon the whole disposed to believe the simple molecule to be of uniform size, ... its diameter appeared to vary from 1/15,000 to 1/20,000 of an inch.

So, with his microscope, he estimates the molecule size at from 1.7 to 1.3μm. A footnote adds *While this sheet was passing through the press ...* he asked the lens maker Dollond to look at *Equisetum* spores, whose surface he had earlier noted released "molecules,"

... with his compound achromatic microscope, having at its focus a glass divided into 10,000ths of an inch, upon which the object was placed; and although the greater number of particles or molecules seen were about 1/20, 000 of an inch, yet the smallest did not exceed 1/30,000th of an inch.

So, with Dollond's microscope, these particular molecules were mostly 1.3μm, with some estimated at .85μm.

Brown prudently concludes,

I shall not at present enter into additional details, nor shall I hazard any conjectures whatever respecting these molecules ... .

H. Brown's Concluding Remarks

In the final paragraphs of the paper, Brown returns *... to the subject with which my investigations commenced, and which was indeed the only object I originally had in view ...*, namely whether the larger particles acted upon the ovule. *My endeavors, however, to trace them, ... was not attended with success ....* He returned to this problem, with more success, a few years later (Section IV). The paper ends with establishing his priority. He notes: *The observations, of which I have now given a brief account, were made in the months of June, July and August, 1827.* He mentions people to whom he showed the phenomenon (he soon traveled to Europe, and demonstrated it there) and people who had made related observations in the past (the phenomenon was first seen by Leeuwenhoek, and remarked upon by many later microscopists —see comments by Nelson[16]) to but fell short of his results in some way .

Brown issued an addendum the following year[23], *Additional Remarks on Active Molecules*,

... to explain and modify a few of its statements, to advert to some of the remarks already made, either on the correctness or the originality of the observations, and to the causes that have been considered sufficient for the explanation of the phenomena.

He rejects the notion that the molecules are animated, he regrets having introduced hypotheses such as larger objects being made out of molecules, distances himself from the notion that the molecules are identically sized, rejects some explanations of the motion. He says they are *... motions for which I am unable to account.*

He describes an experiment designed to put to rest the idea that it is evaporating water, or interaction among the particles, which produces the motion, He shakes a mixture of oil and water that has previously been filled with particles, obtaining small drops of water surrounded by oil, some of which contain only one particle, and notes that the motion is unabated and continues indefinitely since the water does not evaporate.

He concludes once again by *... noticing the degree in which I consider those observations to have been anticipated*, and discussing other people's earlier work.

IV. BOTANY

A. Early Pollen Research

Unbeknownst to Brown, the mechanism of fertilization of the ovule by pollen he had been looking for had been observed by accident in 1822 by the Italian optical designer, astronomer and botanist Giovanni Battista Amici (1786-1863). Amici was looking at a hair on a stigma[35]:

I happened to observe a hair with a grain of pollen attached to its tip which after some time suddenly exploded and sent out a type of transparent gut. Studying this new organ with attention, I realized that it was a simple tube composed of a subtle membrane, so I was quite surprised to see it filled with small bodies, part of which came out of the grain of pollen and the others which entered after having traveled along the tube or gut.

Thus, what is now called the pollen tube was discovered. Brown became aware of this, and launched an investigation of the germination of pollen grains in orchids in 1831.