The Salt Finger Experiments of Jevons (1857) and Rayleigh (1880)*

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ABSTRACT

Over a century before Melvin Stern discovered salt fingers, W. Stanley Jevons performed the first salt finger experiment in an attempt to model cirrus clouds. Remarkably, he seemed to realize that a more rapid diffusion of heat relative to solute played a role in the experiments. However, he oversimplified the physics and incorrectly assumed that the "interfiltration of minute, thread-like streams" was a general result of superposing heavy fluid over light fluid. Interestingly, Lord Rayleigh became aware of these experiments more than two decades later. Here newly discovered evidence is presented that Rayleigh repeated the Jevons experiments at the Cavendish Laboratory in Cambridge in April 1880. The results led him to initiate the study of buoyancy effects in fluids by formulating several stability problems for a stratified, but nondiffusive, fluid. He thus discovered the expression for the buoyancy frequency of internal waves and the convective phenomenon now known as the Rayleigh–Taylor instability. His neglect of diffusion meant that he missed an opportunity to discover double-diffusive convection; though given the limited knowledge of fluid physics at the time, this is understandable. The historic record shows a tortuous intellectual path in which observations of clouds led to an inappropriate experimental demonstration of salt fingers that inappropriately motivated the theoretical discovery of the frequency of internal waves, which was ignored until well into the next century.

1. Introduction

Melvin Stern (1960) is credited with the discovery of double diffusion. Double-diffusive convection arises when two density-affecting components (heat and salt) have different molecular diffusivities or conductivities and one component possesses a gravitationally unstable distribution, though the overall large-scale density distribution is stable. Salt fingers appear when warm, salty water lies above colder, fresher water. The convection occurs in the form of narrow, vertically aligned cells (fingers), which exchange heat, but not salt, laterally. This heat transfer cools the salty water causing it to sink and warms the fresher water, causing it to rise. The process is common in the subtropical ocean, where salt fingers a few centimeters wide and about one meter long are believed to play an important role in mixing (Schmitt 1994). Stern's theoretical derivation, and corroborating experiments, occurred in late 1959 in Woods Hole, Massachusetts. Faller (1992) records the excitement of the day of the finding. It represents one of the few instances in oceanography where a phenomenon was discovered without the motivation of preceding experiments or observations, though the prior work of Stommel et al. (1956) certainly played a role.

However, it has been recognized recently that some experiments performed about 100 years earlier were actually the first demonstration of salt fingers (Veronis 1981; Charnock 1983; Schmitt 1994). These were reported by W. Stanley Jevons in 1857, in the *London, Edinburgh and Dublin Philosophical Magazine and Journal of Science.* His experiments seem to have elicited no interest until an 1883 paper by Lord Rayleigh. Recent examination of Rayleigh's laboratory notebooks reveals that he repeated the Jevons experiments in 1880, though no mention is made of this in the published paper. While Jevons came close to understanding the double-diffusive character of the instability, he unfortunately oversimplified the problem and assumed that all heavy-over-light convection would take the form of "minute, thread-like streams." This was sufficient to distract Rayleigh from the opportunity to understand double diffusion, though he did treat other important problems in stratified fluids. One can only speculate that a full discussion of the experiment between these two distinguished scientists would have allowed Rayleigh to discover the process of double diffusion. However, Jevons died, under somewhat mysterious circumstances, between the time Rayleigh performed his analysis and published his paper, and no record of communication between them has been found. Rayleigh's work, though one of the earliest considerations of buoyancy effects in fluids, was largely ignored until well into this century. The following is a

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report on this apparent "cul-de-sac" in the development of our knowledge of convective processes.

2. W. Stanley Jevons

> I have discovered someone whom I had not realized to be very good—namely Jevons. I am convinced that he was one of the minds of the century.
> —John Maynard Keynes to Lytton Strachey (Schabas 1990).

William Stanley Jevons (Fig. 1) was born in 1835 in Liverpool, England, to an iron merchant father and a mother who wrote poetry. He showed an early interest in the sciences, particularly chemistry, biology, and mathematics. A family financial crisis forced him to leave University College, London, to take a position as assayer at the new Royal Mint in Sydney, Australia, in 1854, when he was 19. As one of the few people in Sydney with some university education, he joined the intellectual elite of the rapidly growing city. His skill in chemistry led him to become one of the first photographers in Australia (Burke 1955). While there he also displayed a keen interest in meteorology; this motivated laboratory experiments to model clouds, which are discussed below. After nearly five years in Sydney he returned to England to complete his education. He took up economics and achieved prominence with what was one of the first discussions of an energy crisis (Jevons 1865). He was a professor of logic, mental and moral philosophy, and political economy at Owens College, Manchester, from 1866 to 1876. He suffered from ill health and found the delivery of lectures on such a broad range of subjects so burdensome that he was happy to leave the Owens professorship for a chair in political economy at University College, London. He is regarded as one of the first quantitative economists and is credited with designing one of the earliest "logical engines." Biographical sketches of Jevons are available in Black (1972), Keynes (1951), and Schabas (1990). Black (1972) provides his journal (mainly for his time in Australia) and letters, so it is possible to gain insight into the thinking of this remarkably mature and clearheaded young man. Inoue and White (1993) provide an extensive list of his publications. He was a prolific writer on economics, logic, and the natural sciences.

Our interest, however, is in one of his first published works, which appeared in the *Philosophical Magazine (Phil. Mag.)* in 1857. His position as assayer at the newly established Sydney Mint allowed him time to pursue his own scientific studies, meteorology being a primary focus. Midway through his stay, the article titled "On the Cirrous Form of Cloud" appeared (Jevons 1857). In this paper he describes a laboratory experiment, which must surely be the first "salt finger" demonstration. It is worth quoting from his paper:

FIG. 1. W. Stanley Jevons, age 22, from a photograph taken in Australia, 6 February 1858, probably by himself. (From *A World Ruled by Number: William Stanley Jevons and the Rise of Mathematical Economics*, by M. Schabas. Princeton University Press, Princeton, 1990. Frontpiece.)

> *Exp.* 1. To about 800 grms. of pure water add 2 or 3 drops of hydrochloric acid, and 1 grm. measure of a strong solution of white sugar (spec. grav. of solution 1.15). Warm this to rather above 100°F., and pour the greater portion into an ordinary glass beaker about 5 inches in diameter and 9 or 10 in height (Fig. 1).
>
> This beaker should be surrounded by a second larger one to prevent disturbance of temperature; and a tube-funnel, allowing only a very slow stream to pass, must be placed in it reaching to the bottom, and with a termination like Fig. 2; or with such similar contrivance as shall prevent all violent currents, and allow us to introduce further quantities of liquid without the least disturbance of the strata above.
>
> The remainder of the hot solution of sugar must be added by this funnel; and before this is quite run out, a little pure cold water is to be added, previously prepared, and consisting of 800 grms. of distilled water at the ordinary temperature of the air, with .2 (2/10) of a gramme of crystallized nitrate of silver dissolved in it. The more gradually this stratum is inserted beneath the other, especially at the first, the more distinct will be the result of the experiment. The nicest manage-

> ment, indeed, and the most careful and patient manipulation are necessary in order to prevent any accidental and irregular mixture from taking place, which would confuse the shape of the cloud; but even in this case sufficient cirrous action will subsequently go on, to answer the purposes of our experiment.
>
> A white precipitate of chloride of silver, of the usual cloud-like appearance, will immediately begin to form, and from the first will present an entirely cirrous character. Small streams in the form of threads or curiously shaped bands will be seen passing from one stratum into another, and often curving about in the most complicated and beautiful manner. After a time the middle of the glass will be filled by a dense and confused but still fibrous mass of cloud, which will probably soon extend itself to the bottom; but there will now also be seen with the greatest distinctness, numbers of these small parallel threads ascending and reaching nearly to the surface of the top stratum, of considerable length, and ending in evanescent points.
>
> The slightest circular motion or disturbance communicated to the strata will cause these fibres to assume all sorts of curved and flexuous forms, which, however, in general still maintain their parallelism. And it is upon the exact resemblance of the cirrus, that the probability of the truth of this theory must be allowed principally to rest.
>
> It is evident that the cloud of chloride of silver is produced by the gradual mixing of the upmost and lowest strata containing respectively hydrochloric acid and nitrate of silver, thus representing closely the precipitation of watery particles by the mixture of portions of moist air of different temperatures. It remains then only to consider the manner and cause of mixture.
>
> The addition of one-eight percent. of sugar solution was found to raise the specific gravity of water by about 4-10,000dths (that is, from 1.0000 to 1.0004 at 60°F.); but when heated to about 100°, its density is not more than about .994 or .995, so that at this temperature it will lie in a separate stratum above pure water at 60°.
>
> The parts of these strata, however, which are immediately in contact, soon communicate their heat and tend to assume a mean temperature; and it is evident that whenever this is the case, the portions of liquid containing sugar must always be slightly denser than those that are pure, and must consequently sink below and displace the latter.
>
> We shall thus have portions of the upper stratum continually sinking into the lower, and corresponding portions of the lower rising through the upper; and this movement, as the experiment demonstrates, takes place by an *interfiltration of minute, thread-like streams.*
>
> (It is evident that the difference of temperature of the strata in this experiment is not a material point, being simply a means employed to enable us to lay one stratum upon another of a slightly greater density when of the same temperature, so that we may afterwards observe the mixing process and change of place in the most gradual manner possible.)
>
> *Exp.* 2. Let the first experiment be now repeated in exactly the same manner, with the exception of adding the sugar to the lowest stratum instead of to the highest, as before.
>
> The appearances will now be totally different; but little cloud at all will be seen to form, even after a considerable length of time; and whatever may happen to be caused by accidental disturbance will lie in a uniform or streaked flat sheet at the surface where it is produced, until it finally subsides to the bottom by its own density.
>
> These two experiments exhibit a most striking contrast; and the only difference of conditions being in the inversion of the light and dense fluids, we are at once led to the conclusion, that different portions of liquids may, from the effects of very slight differences of specific gravity alone, be caused to mix and pass into each other in the form of minute streamlets, which, if rendered visible, as by the formation of a precipitate along their sides, present exact resemblances in form to the fibres of cirrous cloud.

Experiment 1 (Fig. 2) is, without a doubt, a demonstration of salt (sugar) fingers. (Sugar diffuses at about 1/300 the rate of thermal conduction, so sugar solutions can readily form fingers.) From the data supplied, we can estimate the density ratio (thermal density effect/sugar density effect) to be about 15, well within the theoretical range of 1 to 300 necessary for heat–sugar fingers to occur. The description of the "interfiltration of minute, thread-like streams" that maintain their parallelism despite disturbances is certainly an accurate portrayal of the process. An experienced laboratory investigator will appreciate his technique and advice for setting up the fluid layers. It is also noteworthy that he took the time to perform a control experiment, with the sugar in the underlying cold water, which was completely stable.

Most amazingly, he comes close to correctly understanding the role of the difference in diffusivities for heat and sugar when he states that the parts of the strata in immediate contact "soon communicate their heat and tend to assume a mean temperature; and it is evident that when ever this is the case, the portions of liquid containing sugar must always be slightly

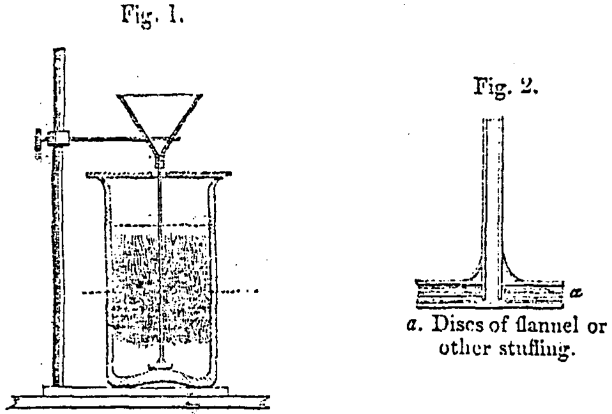


FIG 2. A sketch by Jevons of the experiment described in his 1857 article in the *Philosophical Magazine*.

denser than those that are pure and must consequently sink below and displace the latter." An implicit assumption that heat diffuses faster than salt is apparent. The sentence is a reasonably accurate description of the salt finger instability and represents extraordinary physical insight for the time.

However, he clearly goes off track in the parenthetic remarks prior to the description of experiment 2. There he maintains that the temperature difference was not important, being simply a means to facilitate the superposition of heavy over light fluid. In fact, the large-scale stability of the water column is maintained by the temperature difference and actually increases as the fingers grow and redistribute the destabilizing solute. Elsewhere in the article he emphasizes his belief that convection in general should take the form of slow, "minute streamlets," apparently believing that large-scale overturning was actually an artifact, resulting from deficiencies in experimental technique. This oversimplification of the physics was sufficient to distract him, and later Rayleigh, from understanding double diffusion, although he came very close in the earlier comment. He apparently thought that the thermal conduction was only vertical, not appreciating that the descending "stream-lets" could loose heat laterally. His main goal was to develop a theory for cirrus clouds, and he was quite convinced that the slow convection process that he had demonstrated was the true explanation. The silver chloride precipitate that he used for flow visualization was an obvious trick for an assayer (and photographer); silver nitrate would be readily available from tests for gold purity.

Aside from the article in the *Philosophical Magazine,* he published a longer discussion of these experiments, and additional experiments attempting to explain other cloud forms, in the *Sydney Magazine of Science and Art* the following year (Jevons 1858). There he describes another experimental apparatus, the "section glass," which contained fluid between two glass plates a short distance (1/3 inch) apart (Fig. 3). This apparatus anticipated the Hele Shaw cell by 40 years (Hele Shaw 1898). The description of the "sugar" finger and statically stable experiments is identical to that given in the *Philosophical Magazine* article. One of the other experiments, in which fluid of intermediate density is introduced between two strata, can be identified as salt fingering. Jevons notes that the "curose (sic) threads obtained in the section glass are much larger and coarser" than those obtained in a round glass vessel, a result consistent with the Hele Shaw theory of Veronis (1987), if the gap between the glass plates is less than about three times the finger width. In addition, at least one of the *Sydney Magazine of Science and Art* experiments can be identified as the first demonstration of lateral intrusions, in which density-compensating horizontal gradients of heat and solute allow the development of horizontal motions driven by the double-diffusive convection. In particular, figure VIII in Fig. 3 is a sketch of the introduction of cool freshwater between a layer of warm sugar water and cold sugar water, which can support fingers on the upper interface of the injected fluid. The possibility of driving lateral motions by the flux convergence due to salt fingers was not recognized until Stern (1967) theoretically predicted that the process could be an important lateral mixing agent in the ocean. The Jevons sketches, with the tube source of introduced fluid, strongly resemble the modern experimental investigations of the intrusion process by Turner (1978).

It is interesting to note that the site of these experiments, the Sydney Mint, still exists; it is one of the oldest government buildings in Australia. It currently serves as a numismatic museum. However, records indicate that the rooms devoted to the assayers offices and laboratories of Jevons's time were destroyed for renovations in the 1950s (David Dolan 1994, personal communication).

Jevons was gifted with a powerful physical intuition. In the *Sydney Magazine of Science and Art* article he displays a good understanding of how heat and water content affect the density of air and how precipitation releases heat in the upper atmosphere, thereby generating buoyancy capable of driving convection. In addition to the cloud experiments, the latter article has comments on lightning that show he understood that it was charge separation due to cloud motion that caused lightning and not charges that caused cloud motion, a theory popular at the time. Of interest to oceanographers, he also heaps scorn on Matthew F. Maury's theory on wind:

> The new work of Lieutenant Maury on the "Physical Geography of the Sea" contains one of the worst examples of these vicious theories; for the safest conjecture which he can offer, as the result of the splendid system of observation of which he is the head, is that the winds are probably directed in their course by terrestrial magnetism. As a general rule we may look upon all electrical theories as utter nonsense.

We must also give credit to Jevons for his observational skills. The journal he kept in Australia is full of descriptions of the geology, meteorological phenomena, and flora in the areas he visited. When he discovered that there were no routine meteorological measurements being made in Sydney, he began them himself. After two years of twice daily observations he convinced the government to take them on. Perhaps the most impressive thing about these accomplishments was his youth; when he published these experiments, he was only 22! (Fig. 1)

Jevons was confident of his ideas on clouds. In a letter dated 9 October 1858 to his cousin Dr. Henry Roscoe (a chemist) he states (Black 1972):

> By the bye, it rejoiced my heart to see my last paper on Clouds in the fore most part of the *Phil. Mag.* for which I have a high respect. As yet I do not know that

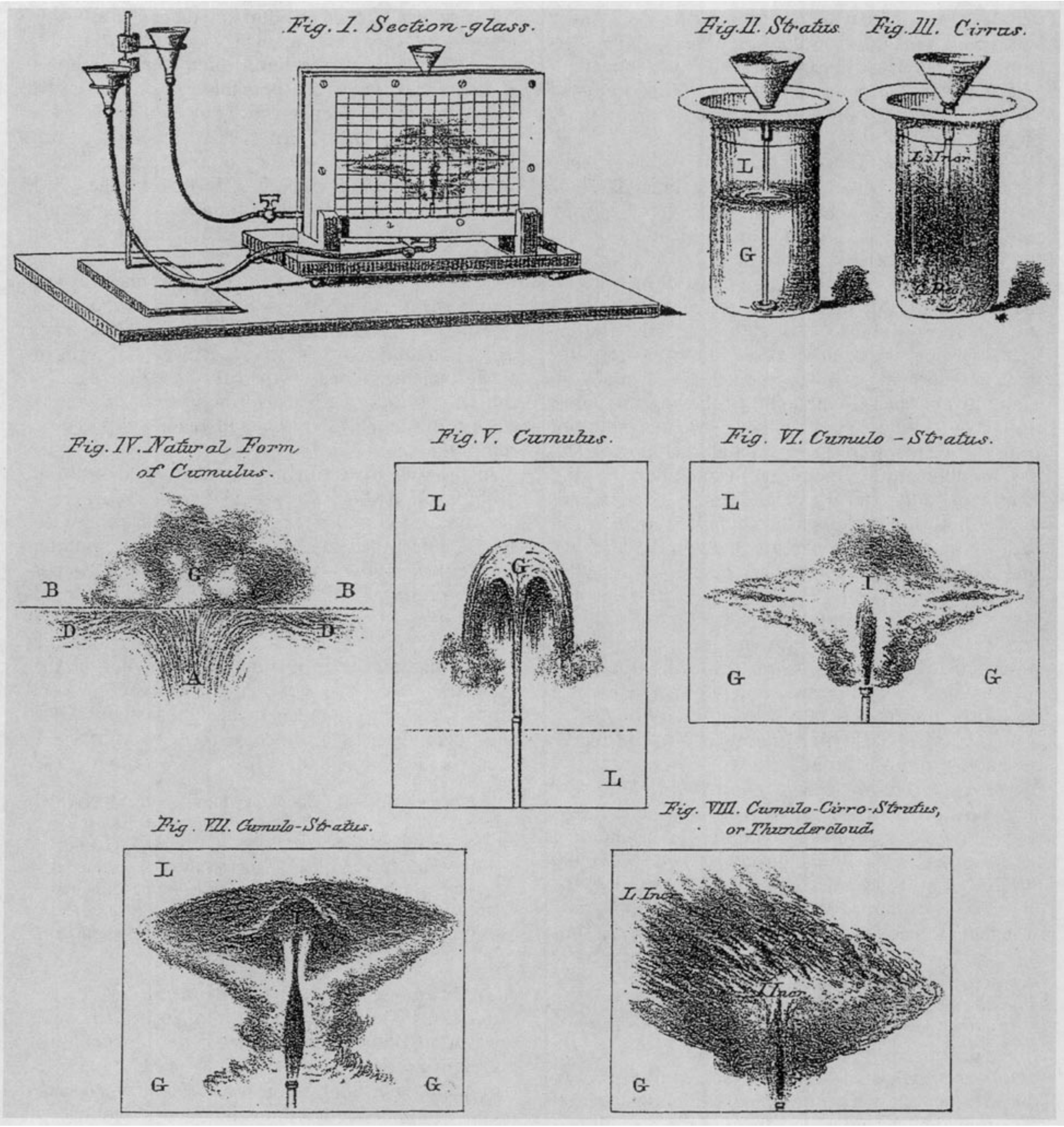


Fig. I. Section-glass.

Fig. II. Stratus.

Fig. III. Cirrus.

Fig. IV. Natural Form of Cumulus.

Fig. V. Cumulus.

Fig. VI. Cumulo-Stratus.

Fig. VII. Cumulo-Stratus.

Fig. VIII. Cumulo-Cirro-Stratus, or Thundercloud.

FIG. 3. Experimental figures from Jevons's 1858 article in the *Sydney Magazine of Science and Art*. Figure 1 shows the "section glass" (two sheets of glass 1/3 inch apart, as in a Hele-Shaw cell). Figures II and III show the statically stable and sugar finger experiments as in the *Phil. Mag.* article. Figure IV is his sketch of a cumulus cloud. Figure V shows a jet of slightly dense water carried upward by its momentum. Figures VI and VII show two stably stratified layers with a jet of intermediate density fluid introduced from below. Figure VIII represents a jet of cold fresh fluid injected between warm sugar and cold sugar layers. Thus, it can support fingers at the upper interface.

any notice has been taken of my views, but I am convinced in my own mind that I have lead the way to a rational mode of treating atmospheric subjects; I have a perfect belief in the theory of the Cirrous, and have no doubt that my views of the cumulostratus, thundercloud and even of the electricity of the latter will prove correct. I am quite reconciled to the expectation that every thing which I have said will be attributed to some previous writer or adopted by some subsequent one, so that I shall be quite shorn of all credit.

As it turned out, the work seemed to have elicited virtually no response, aside from minor criticism from Rev. W. Scott, an Australian astronomer and meteorologist. He did correspond with Sir John Herschel to inform him about the work in July 1861, and received encouragement. However, by the mid-1860s Jevons was well into his career as an economist and did not maintain his meteorological interests (though he did later attempt to relate business cycles to the sunspot cycle). Jevons struggled early on to establish himself, was eventually successful, and was elected a Fellow of the Royal Society in 1872 (Fig. 4). He was much more interested in, and successful at, research than teaching. Indeed, he found his professorial duties increasingly irksome and resigned his position in 1880 to devote his energies entirely to his research and writing. Unfortunately, he drowned two years later while swimming near Hastings, three weeks short of his 47th birthday. His death was somewhat mysterious, as he was under doctor's orders not to swim. At the beach with his family, he had informed his wife that he was returning to the house, but actually went over to an adjacent cove, which was considered dangerous, for his swim. These circumstances and a statement by his wife that "his health was an increasing anxiety and his mind so encumbered with all he wanted to do that he seemed to feel life grow more and more hard to him every year" (Schabas 1990), has led to speculation that his death was a suicide (Huppert 1994, personal communication; Schabas 1994, personal communication). However, his poor health, and a possible heart attack due to the shock of cold water represent a simpler explanation of his demise, especially since he was an experienced swimmer and was actively working on a number of projects. It is a sad irony that had he lived just another year or so he would have had the satisfaction of public recognition of his earliest scientific work by the most prominent English physicist of the time, Lord Rayleigh.

3. Lord Rayleigh's 1883 paper

Serious consideration of the Jevons work on clouds did not occur until 1883, when Rayleigh published a theoretical analysis of the two experiments described in the *Philosophical Magazine* article. Lord Rayleigh (John William Strutt 1842–1918), of course, was one of the most accomplished scientists who ever lived. He was seven years younger than Jevons, Cambridge educated, and Senior Wrangler in the Mathematical Tripos of 1865 (besting the economist-to-be Alfred Marshall) (Fig. 5). He succeeded his father as the third Baron Rayleigh at the age of 31. He used his wealth to great scientific advantage, devoting his life to the pursuit of a wide variety of topics in optics, acoustics, electricity, fluid dynamics, and chemistry. He followed Maxwell as Cavendish professor of experimental physics at Cambridge University for five years, received the Nobel Prize in 1904 for the discovery of argon, and was secretary (editor) of the Royal Society for many years and later its president. He is reportedly one of the most highly cited nineteenth century scientists today, because of the large number of topics he addressed in his career.

FIG. 4. Stanley Jevons in later life. (from *Encyclopaedia Britannica: Micropedia,* Vol. V, Encyclopaedia Britannica, Chicago, 1977, p. 552)

In 1883 he published an "Investigation of the character of the equilibrium of an incompressible heavy fluid of variable density" in the *Proceedings of the London Mathematical Society.* Rayleigh's paper, which he notes as being motivated by the Jevons experiments, is a short mathematical treatment of the stability of a stratified fluid with density either increasing or decreasing with depth. The cases considered included two superposed layers, exponential stratification, and two layers with a transition zone. He neglects diffusion, assuming that the density of every particle remains unchanged. Viscosity is also ignored, and he makes no attempt to relate the theory to observations.

Rayleigh finds that in the stable, continuously stratified case, there is a "limit on the side of rapidity of vibration but none on the side of slowness." This limit is defined by

FIG. 5. John W. Strutt, age 28, from a wet colodion photograph by himself in 1870. (From the *Life of John William Strutt, Third Baron Rayleigh,* by R. J. Strutt. University of Wisconsin Press, Madison, 1968. p. 75)

$$n^2 = -g\beta, \quad (1)$$

where $\beta = \sigma^{-1}d\,\sigma/dz$ and σ is the density.

It is surprising to see the expression for the buoyancy frequency of internal waves derived over 40 years prior to Brunt (1927) and Väisälä (1925)—even more so because the notation is so standard! As Gill (1982) has pointed out, Rayleigh certainly deserves credit for priority in this discovery.

In the two-layer case of heavy fluid over light, Rayleigh finds that the growth rate "is greater the smaller the wavelength," according to the relation

$$n^2 = gk\frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2}, \quad (2)$$

where n is now the growth rate and k the wavenumber (inverse wavelength). This result was not rediscovered until 1950 by Sir Geoffrey Taylor (Taylor 1950), who treated the case of arbitrary accelerations (in connection with the development of the atomic bomb). Now known as the Rayleigh–Taylor instability, it is an important process in plasma dynamics, super-novae explosions, and heavy-nuclei collisions (Petrasso 1994). Lewis (1950) performed the first corroborating experiments for this instability.

The preference for small scales in the two-layer unstable case is an obvious point of similarity to Jevons' "minute, thread-like streams." However, Rayleigh neglects to discuss this, or any other physical application of the theory. Indeed, the only reference to Jevons is contained in the footnote to the title of his 1883 paper. The footnote states:

> These calculations were written out in 1880, in order to illustrate the theory of cirrous clouds propounded by the late Prof. Jevons (*Phil. Mag.* xiv. p. 22, 1857). Pressure of other work has prevented me hitherto from pursuing the subject.

If the Jevons results were common knowledge, it might be reasonable to assume that the reader would draw the obvious connections between theory and experiment. However, this seems unlikely, as the experiments had been published more than 25 years earlier and Jevons was known as an economist. While it may be that such a spare style was typical of Rayleigh's mathematical papers, one comes away with a sense of incompleteness with the lack of motivation or discussion of applications of the theoretical results.

3. Rayleigh–Sidgwick Salt Finger Experiments of 1880

To further explore Rayleigh's motivation for the theory, I examined his original laboratory notebooks. These are available in the Rayleigh Collection at the Phillips Laboratory Research Library, Hanscom Air Force Base, Bedford, Massachusetts. The notebooks are described by Howard (1964a). There are 12 notebooks in Lord Rayleigh's hand and one by his sister-in-law Eleanor M. Sidgwick. The collection also includes the original handwritten manuscripts of many of Rayleigh's papers, though not the 1883 paper of interest here. The Sixth Notebook covers the period 1876–1889 and reveals that he was working on water jets, acoustics, optics, color perception, magnetization, polarimetry, and a variety of other topics. However, no mention of Jevons or any notes relating to the paper were found in Rayleigh's Sixth Notebook. Fortunately, the Sidgwick Notebook provides one page of highly relevant material.

Eleanor Balfour (1845–1936; Fig. 6), sister of Evelyn Balfour, Lord Rayleigh's wife, and sister of Prime Minister Arthur Balfour, married Henry Sidgwick in 1876 (Howard 1964b). Sidgwick was lecturer and professor of moral philosophy at Cambridge University and wrote many works on morals, ethics, and political economy. Eleanor had accompanied Rayleigh and her sister on a boat trip on the Nile, during which Rayleigh helped her work through a reading course in mathematics while he began to write *The Theory of Sound* (Rayleigh 1894). She was a strong advocate of education for women and was treasurer and principal of Newnham College, Cambridge University. She dis-

FIG. 6. Eleanor M. Balfour (later Sidgwick), age 25, from a photograph by John W. Strutt (later Lord Rayleigh) in 1870. (From *Mrs. Henry Sidgwick,* a Memoir by her niece Ethel Sidgwick. Sidgwick and Jackson Ltd, London, 1938. p. 22)

played interest in, and talent for, physics and mathematics, and enjoyed discussing science with Rayleigh. While Rayleigh was at the Cavendish, she served as his laboratory assistant. She helped with the redetermination of the value of the ohm and was coauthor of five of his dozen papers on electrical standards and acknowledged as coworker in three others. After Rayleigh returned to his home at Terling Place, he would often arrange to perform experiments requiring assistance when she would be visiting (Howard 1964b). Her notebook covers the period from April 1880 to March 1881, early in Rayleigh's tenure at the Cavendish. Figure 7 is a copy of the original notebook entry, which is on the first page of the notebook. My transcription follows:

> Cavendish Laboratory April 1880
>
> We repeated several times the experiment of W. W. S. Jevons (see *Phil. Mag.* for July 1857) on the formation of cirrous clouds. A glass funnel connected with a straight glass tube by a short piece of india rubber tube was used and the current, which had to be very slow, regulated by nipping the india rubber tube. The experiment seemed to answer best when the lower end of the tube rested on a small disc of thick flannel laid on the bottom of the beaker. The apparatus in other respects was similar to Jevons. The effects obtained resembled those described by him only generally the filaments seemed not fine enough to correspond with his description and drawing. In all cases moreover the extremities of the filaments were expanded in a mushroom like form. We also tried the experiment with water coloured with aniline and uncoloured water—still adding the sugar solution to that which was ultimately to fall. The appearance produced was much the same, but visible only in the uncoloured liquid.

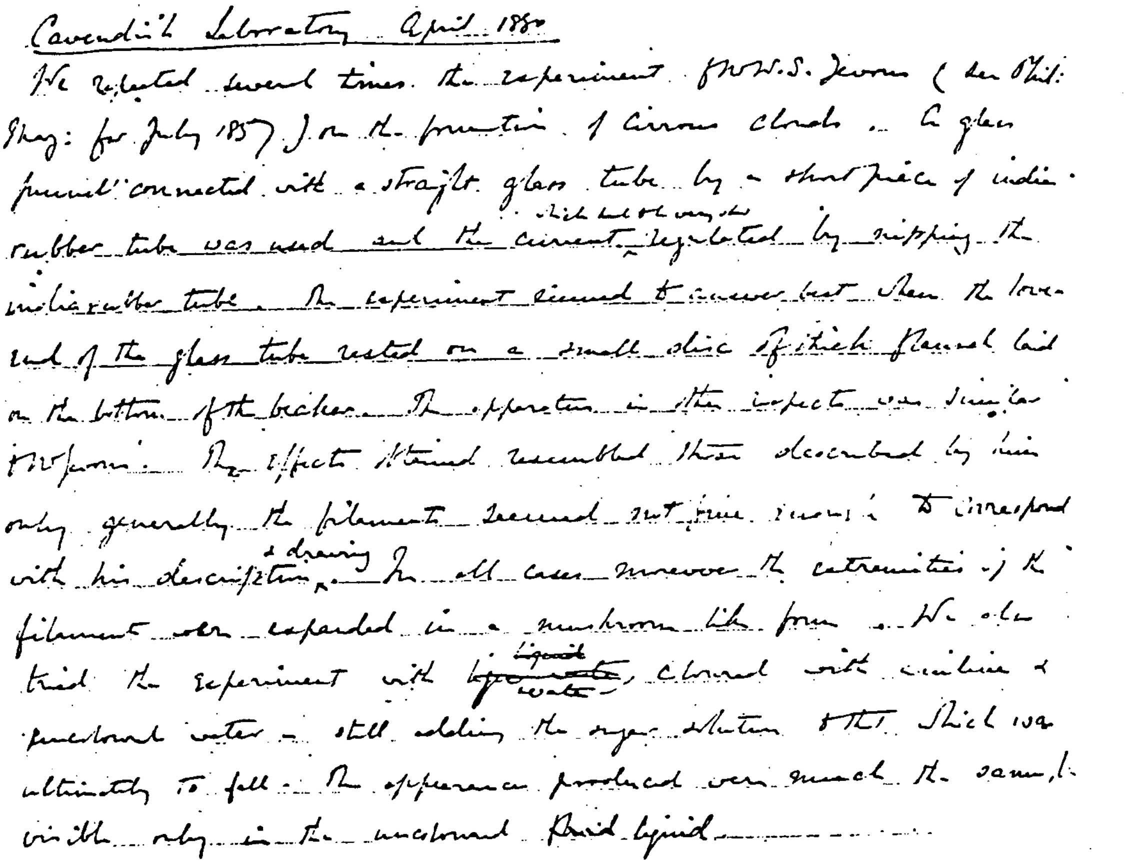
The foregoing entry provides proof that Rayleigh had taken the time to repeat the Jevons experiments. The text implies that they duplicated Jevons's visualization technique (silver chloride precipitate) and also used a dye as a simpler means of observing the flow. The apparently wider fingers they observed could have been due to a weaker vertical temperature gradient, though the dependence is only on the fourth root of the temperature gradient (Stern 1960). However, it is difficult to judge the significance of this statement, since neither Jevons nor Rayleigh/Sidgwick quantified the scale of the fingers. The "mushroom like form" they report is likely the same as Jevons's "curiously shaped bands . . . curving about in the most complicated and beautiful manner." Such structures have been corroborated by recent laboratory experiments (Taylor and Bucens 1989) and numerical models (Shen 1989) on salt finger convection. That Rayleigh performed his own salt finger experiments makes it even more surprising that he missed the role of diffusion in the instability. It is also puzzling that he makes no mention of his experiments in the 1883 paper. Presumably, he decided that Jevons's description was sufficiently complete and accurate.

4. Discussion

While this evidence of a second set of salt finger experiments by Rayleigh at the Cavendish in April 1880 is of historical interest, it provides no insight into the question of how Rayleigh came to be aware of the Jevons work. No correspondence between them exists in the archives of either Jevons (McNiven 1983) or Rayleigh (John Armstrong 1994, personal communication). Three scenarios can be suggested:

1) Jevons mentioned the experiments to Rayleigh in conversation at a function of the Royal Society. Jevons became a Fellow in 1872, Rayleigh in 1873. Jevons would certainly have identified Rayleigh as having a potential interest.

2) Others alerted Rayleigh to the Jevons paper. One possibility is his brother-in-law, Henry Sidgwick, who was in the same field as Jevons and knew him and his work (Schabas 1990). However, as "the last of the util-



Cavendish Laboratory April 1880

We repeated several times the experiment of Mr W.S. Jevons (see Phil: Mag: for July 1857) on the formation of Cirrus Clouds. A glass funnel connected with a straight glass tube by a short piece of india-rubber tube was used and the current which was not very [illegible] regulated by nipping the indiarubber tube. The experiment seemed to answer best when the lower end of the glass tube rested on a small slice of thick flannel laid on the bottom of the beaker. The apparatus in other respects was similar to Mr Jevons'. The effects obtained resembled those described by him only generally the filaments seemed not fine enough to correspond with his description & drawing. In all cases moreover the extremities of the filaments were expanded in a mushroom like form. We also tried the experiment with ~~[illegible]~~ liquid water coloured with cochineal & [illegible] water – still adding the sugar solution to that which was ultimately to fall. The appearance produced was much the same, [illegible] visible only in the uncoloured fluid liquid

FIG. 7. The first entry in the Eleanor Sidgwick Notebook in the Rayleigh Collection. (Phillips Research Library, Hanscom Air Force Base, Bedford, MA.)

itarians" and in the same school of thought as J. S. Mill, he might not have been sympathetic to Jevons's new quantitative economics, nor likely to take an interest in cloud experiments. Sir John Herschel, who was aware of the Jevons papers, died in 1871, so was not a likely conduit to Rayleigh.

3) Rayleigh came across the paper while reading back issues of *the Philosophical Magazine.* This was his favorite journal (Howard 1964a), he read widely, and he maintained a collection of the serial in his home [and would not lend it out even to Lord Kelvin! (Strutt 1968)].

However Rayleigh came to know about the Jevons work; the timing of his paper, three years after performing the work and one year after Jevons's death, is very curious. Having duplicated the experiments and developed the theory in 1880, he may have deferred publication in order to discuss the results with Jevons. Prevented from exploring the topic with Jevons by his untimely death, Rayleigh simply decided to publish what he had. One can only speculate that with greater opportunity for exchange between these two distinguished scientists, much greater insight could have been achieved. However, Jevons had a reputation as a rather reclusive character (Keynes 1951) and may have been difficult to approach. Moreover, Rayleigh was a keen observationalist and could have realized the role of thermal conduction in the process himself, especially given Jevons's marvelous hint and having witnessed the fingers in his own laboratory. Had Jevons survived long enough to discuss the experiments with Rayleigh they could well have reached a more complete understanding. How much more would we know about double diffusion if it had been discovered over a century ago instead of just three decades?

However, given the lack of knowledge of fluid dynamics in the last century, it might not have made any difference if Rayleigh had come to understand the physics of double diffusion. After all, his derivation of the buoyancy frequency of internal waves was overlooked for years, and the Rayleigh–Taylor instability was not rediscovered until 1950. Progress in fluid dynamics in this century has been heavily dependent on experimental, observational, and computational tools that did not exist then. Rayleigh makes reference to the 1883 paper (but not the Jevons work) in his much later treatment of Bénard convection, specifically recognizing it as the inviscid case of the more general problem (Rayleigh 1916). Indeed, one cannot fault Rayleigh's logical development of the theory, even if the motivating experiments were misinterpreted. The 1883 paper treated inviscid, nondiffusive, stable and unstable stratifications. The 1916 paper added viscosity and thermal diffusion (though the experiments of Bénard were actually affected by surface tension). The addition of a second buoyancy-affecting solute with a different diffusivity would have been a logical next step. Perhaps if Rayleigh had focused more on fluid dynamics he might have had time to realize that step and also appreciate the true nature of Jevons's original experiments, which were one of the first demonstrations of buoyancy effects in fluids.

Finally, it is worth noting the tortuous intellectual path to an apparent dead end that these papers represent. Jevons attempted to model atmospheric convection with an inappropriate experimental demonstration of salt fingers, which in turn inspired Rayleigh to discover the buoyancy frequency of internal waves and the conditions for the Rayleigh–Taylor instability. These results were then overlooked until well into the next century, with the original motivating experiment taking the longest time to rediscover! Perhaps this shows that observationalists, experimentalists, and theoreticians have always had difficulty understanding one another. More generously, the unique perspective of each scientist leads to partial truths, and a certain amount of serendipity and the passage of time are necessary to synthesize knowledge in any one area of science.

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