newsletter

OF THE JAMES CLERK MAXWELL FOUNDATION

Issue No.3 *Spring 2013*

The James Clerk Maxwell Telescope

by PROFESSOR DAVIS, B.SC., M.SC., D. PHIL. DIRECTOR, JAMES CLERK MAXWELL TELESCOPE

The name James Clerk Maxwell has a deep resonance for astronomers. Most experimental sciences proceed by perturbing in some way the system under study and observing the result: in the Large Hadron Collider, for example, elementary particles are smashed into each other at high energy and new phenomena are discovered that reveal the fundamental nature of the universe. In astronomy, however, classical experiments such as this are not possible and the only observational tool we have is to study the light we receive from distant objects. Because we use light waves as our messenger, modern observational astronomy is firmly grounded in Maxwell's electromagnetic theory.

It is therefore my privilege to serve as the Director of the only telescope in the world that is actually named after him. The *James Clerk Maxwell Telescope* (JCMT) – *Figure 1* – is owned by the UK Science and Technology Facilities Council and it is operated as a partnership between the UK, Canada and The Netherlands. Its '*first light*' (the astronomical term for the first observations) was in 1987 and for the ensuing 26 years the JCMT has been the best telescope of its kind in the world.

The JCMT is a submillimetre telescope: that is, we use it to study light with wavelengths slightly less than 1 mm. Observing submillimetre light is a daunting technological challenge (which is precisely why there were no submillimetre observatories before 1987). For one thing, whereas the Earth's atmosphere is transparent to visible light (which is why you can see stars at night), it absorbs most of the incoming submillimetre light. It is water vapour in the atmosphere that is responsible for most of this absorption and the only solution is to locate the telescope at a very high dry site so that there is very little water vapour in the atmospheric column above the telescope. The JCMT is located at an altitude of 4,092m at the summit of Mauna Kea on the island of Hawaii, one of the best submillimetre observing sites in the world and certainly the very best in the northern hemisphere. Imagine trying to do optical astronomy in the daytime on a foggy day in Edinburgh and you will get a sense of the practical difficulty that is intrinsic to this type of astronomy.

We do this, despite the technical obstacles, because submillimetre light carries information about the universe that cannot be obtained in any other way. In particular, submillimetre astronomy is used to study very cold and very distant objects: stars in our own galaxy, for example, form in extremely cold clouds of gas and dust at temperatures of 10 to 20 degrees above absolute zero. The physical process by which this happens is not well understood and we use submillimetre light from such objects to unravel the mystery. Optical light, although technically easier, is not useful for this purpose because the objects are too cold and so do not emit light at visible wavelengths.

Figure 1: The James Clerk Maxwell Telescope

When the JCMT was opened in 1987, it was one of the first submillimetre observatories in the world. It has quite literally blazed the trail since then opening up this new and relatively unexplored niche field in astronomy.

One of the most seminal astronomical discoveries of the decade was made in 1998 when a population of distant but bright submillimetre galaxies was detected – *Figure 2*. Because these galaxies are very distant, we are seeing them as they appeared in the very early universe; and because they are bright in submillimetre light, they must be enshrouded in cold dust. '*Dust*' is a term used by astronomers to describe microscopic solid particles that exist in the vacuum of space: think of smoke particles and you get a better idea. These solid particles are essential building blocks of stars and planets and it turns out that these distant and very early galaxies are heavily laden in dust. In submillimetre light we are seeing the heat signature of this cold dust rather than the individual stars that make up the galaxy. This discovery had a profound impact on our understanding of how galaxies form and evolve.

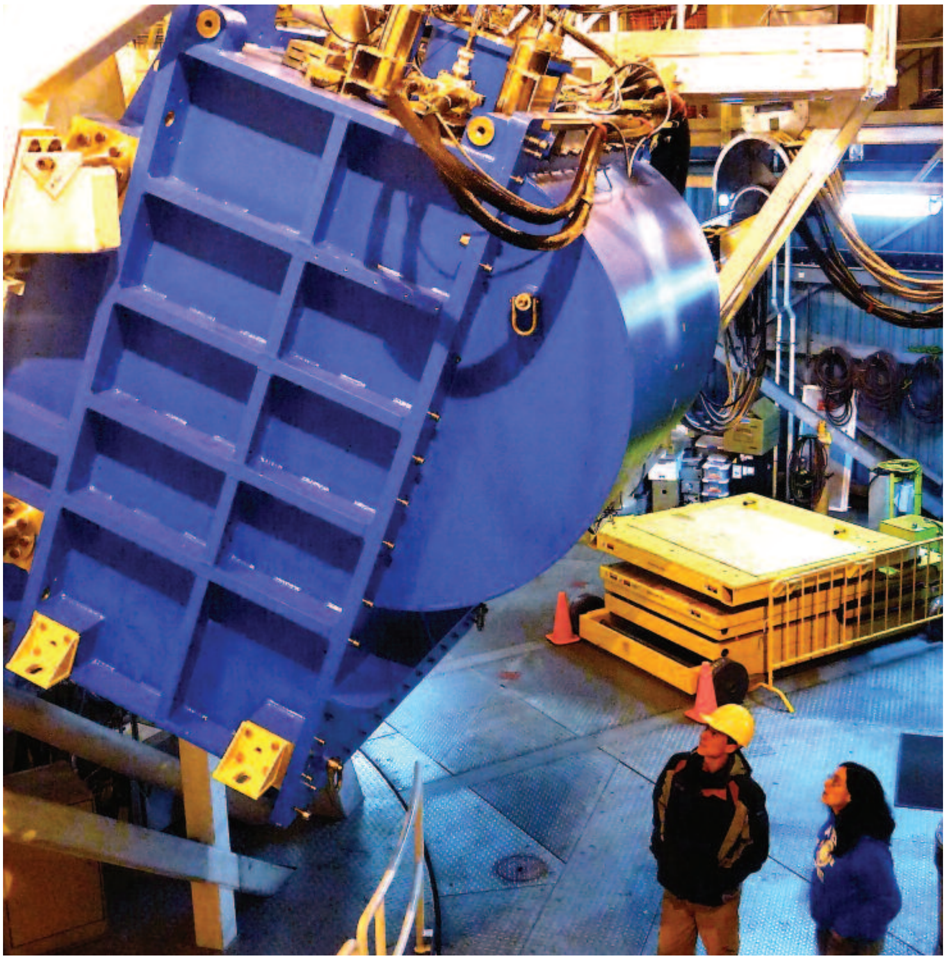

Figure 3: SCUBA-2 – the large size can be gauged by comparison with the onlookers

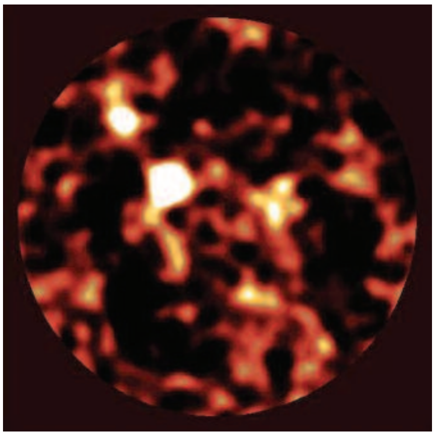

Figure 2: The seminal discovery of 1998 – distant but bright submillimetre galaxies.

Another challenge associated with submillimetre astronomy is the low energy of submillimetre light. For instance, after a long journey to reach the Earth, the fraction of light that does penetrate through the atmosphere to reach our telescope does not carry enough energy to register on the device, in a digital camera, that turns light into an electronic signal. Detecting and processing this type of light requires sophisticated and specialised instruments, often based on emerging technologies. The specialised expertise to build such sensitive equipment exists only at a few laboratories around the world, one of which is in Edinburgh: the UK Astronomy Technology Centre. Many of the JCMT's instruments have been developed there and it is fitting that the James Clerk Maxwell Telescope should retain this link to Edinburgh.

Recently, for example, we commissioned a new camera for the JCMT called '*SCUBA-2*' – *Figure 3*. Built at a cost of nearly £16 million, it encompasses a dizzying array of new and complex technologies. At its heart are eight detector arrays that use a superconducting material to convert the energy carried by the submillimetre light into electrical information that can be computationally processed to produce images. These superconducting arrays operate at just 0.1 degree above absolute zero and although the instrument itself is the size of a small car much of the volume is taken up by the cryogenic system to maintain this extremely low temperature. Since the cosmic background radiation (left over from the big bang) is at 2.7 degrees above absolute zero, we believe the focal plane of *SCUBA-2* is the coldest place in the universe, at least on a continuous basis.

Regrettably, science is not immune from public finances. Following a review process in 2012, a decision was made to terminate our operational funds on 30th September 2014. I am now in the process of seeking a new entity to take over the operation of this wonderful telescope.
http://www.jach.hawaii.edu/JCMT/

Maxwell's Demon

by PROFESSOR AL-KHALILI, BSC, PHD, FINSTP
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The paradox of Maxwell's demon is a simple idea and yet it has consumed many of the greatest names in science and has even spawned whole new disciplines of research – and all because it challenges the second law of thermodynamics, a simple yet profound statement about the transfer of heat and energy and how they can be used.

Imagine a closed box partitioned into two halves by a thick insulating wall. In the middle of this partition is a trap door that opens and closes very quickly when a molecule of air from either side gets close to it and allows that molecule through to the other side of the box – *Figure 1*. All these molecules will be moving around at random and at different speeds; some are faster, others slower. But their combined average speed will correspond to a certain temperature. Thus, on average, there should be as many faster molecules as slower ones crossing each way though the partition and so no temperature difference builds up. If you are worried that faster moving molecules might be able to get through more often than slower ones then you could be right, but this does not affect the argument since as many faster ones should cross from the left to the right as will move back in the opposite direction.

In a public lecture delivered in 1867, James Clerk Maxwell described his famous thought experiment in which a demon sits on the box and can see all the individual molecules of air inside it and knows how fast they are moving. Rather than the trapdoor opening and closing randomly, we now let the demon control when it opens. Although it allows through just as many molecules as before, there is an additional factor to consider here: the demon's knowledge. For it only allows faster moving molecules through from the left chamber to the right and only slow moving molecules from right to left. Armed with this knowledge and with seemingly no extra effort or expenditure of energy (remember that earlier the trapdoor was opening and closing randomly anyway) we find the outcome is now completely different.

Gradually, the right hand side of the box builds up with faster moving molecules and gets hotter, while the left hand side accumulates slower molecules and is therefore cooler. Using the demon's knowledge alone we seem to have created a temperature difference between the two halves, in violation of the second law of thermodynamics, which states that entropy, or the amount of disorder of a system, always goes up unless additional energy is pumped in from outside.

In 1929, Leo Szilárd proposed a version of Maxwell's demon that has since become known as Szilárd's engine. But it was no mere physical process that he seemed to be suggesting was at the heart of the paradox. Instead, he argued that it was indeed the demon's intelligence and knowledge about the state of molecules that made all the difference, just as Maxwell had feared. The paradox could not be resolved with a mechanical device, however ingenious.

Are we then forced to concede that the second law of thermodynamics only holds in a lifeless universe? That there is something magical about life that cannot be encompassed within physics? On the contrary, Szilárd's resolution was a brilliant affirmation of the universality of the second law and the notion of increasing entropy.

You might think that the energy the demon expends in opening and closing the partition, however small an amount is required, is the way it pays the price of lowering the entropy. Such external energy would be the equivalent of winding up a clockwork toy – that is, reducing the entropy of something by carrying out work that has required an earlier increase in entropy from somewhere else. But, if the demon has no information about the state of the molecules and simply opens the partition at random, allowing half the molecules from the left chamber to pass through to the right and half those on the right go in the opposite direction, then the two sides would stay, on average, at the same temperature since as many fast molecules as slow molecules will be passed over in both directions. And yet the demon has still used up the same amount of energy opening and closing the partition. Clearly, the effort required to operate the partition need not have anything to do with the sorting process.

Szilárd argued that the demon must consume energy in the act of measuring the molecules' speeds. Thus, gaining information always comes at an energy cost, energy that is expended in order to organize information in the demon's brain. He was on the right track in as much as information is a vital part of the process of lowering the entropy of the box. But information is nothing more than a particular state of the demon's brain or the memory banks of a computer or indeed any physical system since everything contains information.

The full resolution of the paradox would only become clear later. Think of the brain of the demon starting off as a clean slate devoid of any informational content. This is a very special low entropy state. As the demon gains information about the position and speed of all the molecules in the box, all that random information fills up its brain, raising its entropy. The demon then uses this information to lower the entropy in the box by sorting the air into fast and slow moving molecules. So, while the entropy of the box goes down there is a corresponding rise in entropy in the demon's brain. Of course, Maxwell's demon will never be completely efficient since there will always be some heat dissipation in the process. Thus, the total entropy of the box plus demon always goes up. The Second Law is saved.

The final step is a less obvious one. The demon cannot continue this process of indefinitely: ordering the molecules in the box in order for it to carry out useful work, which causes the two sides to equilibrate again, and then sorting them again. Since the brain of the demon is necessarily finite in size, it can only contain so much information before it runs out of space and maximises its entropy. To repeat the process it must now delete this information about the molecules. And it is this act of erasing information that costs energy – energy the demon must obtain from outside, raising the entropy of its surrounding environment, in compliance with the Second Law of course. ■

Maxwell's Demon, Entropy, Information, Computing (1990), edited by Leff H.S. and Rex A.F. , Princeton University Press

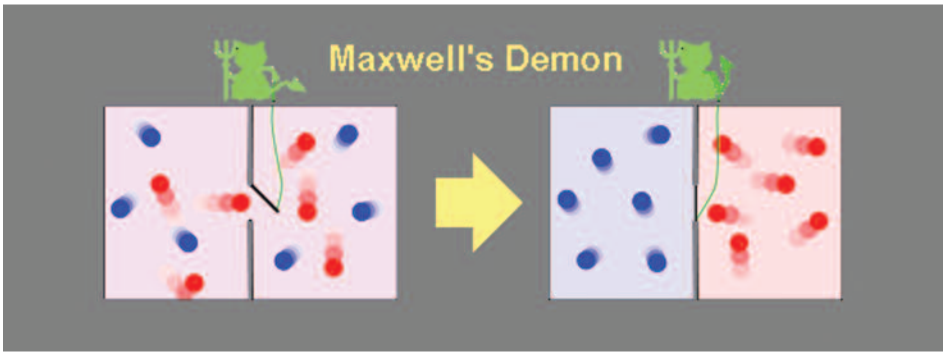

Figure 1: Maxwell's Demon

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Maxwell and the Distribution of Molecular Velocities

By D.O. FORFAR, MA, FFA, FIMA, TRUSTEE OF THE JAMES CLERK MAXWELL FOUNDATION

In 1859, when Maxwell was a professor at Marischal College, Aberdeen, he derived the distribution for the speed of the molecules in a gas (now known as the '*Maxwell-Boltzmann Distribution*') in his paper '*Illustrations of the Dynamical Theory of Gases*'. Maxwell made the assumption that, for an individual molecule, the velocities in the *x*, *y* and *z* directions, were independent. This gave rise to the functional equation:

$$f(u)f(v)f(w) = \phi(u^2+v^2+w^2)$$

with the solution being

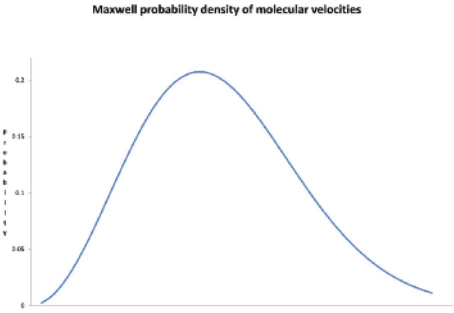
$$f(u) = Ae^{-Bu^2}$$

and

$$\phi(u) = A^3e^{-Bu}$$

e.g. each of the velocities, and *u*,*v* and *w* in the *x*, *y* and *z* directions follows an independent normal distribution. The density function, $f(V)$, for the total velocity, $V=\sqrt{u^2+v^2+w^2}$, is therefore (within a constant) the density function of the square-root of the sum of the squares of three independent standard normal random variables, namely

$$f(V) = \frac{4}{\alpha^3\sqrt{\pi}}V^2e^{-\frac{V^2}{\alpha^2}}$$



It is said that Maxwell had read, in the Edinburgh Review of July 1850, Sir John Herschel's review of "*Quetelet on Probabilities*", which stated:

"Suppose a ball is dropped from a great height given the intention that it should fall on a given mark. Fall as it may, its deviation from the mark is its error and the probability of that error is the unknown function of its square i.e. the sum of the deviations in any two rectangular directions. Now, the probability of any deviation depending solely on its magnitude, and not on its direction, it follows that the probability of each of these rectangular deviations must be the same function of its square. And since the observed oblique deviation is equivalent to the two rectangular ones, supposed concurrent, and which are essentially independent of one another, and is, therefore, a compound event of which they are the simple independent constituents, therefore the probability will be the product of their separate probabilities. The form of the unknown function comes to be determined from this condition, viz., that the product of such functions of two independent elements is equal to the same function of their sum. But it is shown in every work of algebra that this property is the peculiar characteristic of, and belongs only to, the exponential function. This, then, is the function of the square of the error, which expresses the probability of committing that error."*

** That is, the decrease or diminution in one of which may take place without increasing or diminishing the other. On this the whole of the proof depends (Sir John Herschel, 1857).*

The above analysis gives $\phi(x^2+y^2)=\phi(x^2)\phi(y^2)$ and $\phi(x^2)=e^{-ax^2}$ or the normal distribution.

All Maxwell had to do was to translate distances into velocities and two-dimensions to three-dimensions – easy, if you were Maxwell!

JAMES CLERK MAXWELL IN ABERDEEN, 1856–60

The Aberdeen plaque to Maxwell is at:

http://homepages.abdn.ac.uk/npmuseum/Scitour/maxplaq2b.jpg

The article by Dr. John Reid (one of our Trustees) on Clerk Maxwell is at:

http://homepages.abdn.ac.uk/npmuseum/Scitour/Maxwell.pdf

Aberdeen University is also associated with the names of G.P. Thomson (Nobel Prize for Physics, 1937), Frederick Soddy (Nobel Prize for Chemistry, 1921), James Brown (Brownian Motion), R. V. Jones (scientific adviser to Churchill).

http://homepages.abdn.ac.uk/npmuseum/scitourMarischal.shtml

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The birthplace in 1831 of James Clerk Maxwell.

www.clerkmaxwellfoundation.org

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