THE SMALL AND THE LARGE IN PHYSICS

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So, naturalists observe, a flea
Has smaller fleas that on him prey;
And these have smaller still to bite 'em;
And so proceed ad infinitum.
Poetry, a Rhapsody. Jonathan Swift (1726)

An introduction to the range of physics from the very small to the very large in a historical perspective for a general audience.

1. Introduction

The poem of Jonathan Swift epitomizes the question as to whether there is a limit to smallness, or indeed largeness. By the 1700's the applications of microscopes and telescopes to the ever smaller, and larger, were developing fast. Here we first trace some of the early history, emphasizing the close connection between science and technology in all these developments up to modern times.

2. Lenses, Magnifiers and Microscopes

Seneca ∼100 AD noted that "*Letters, however small and indistinct, are seen enlarged and more clearly through a globe of glass filled with water*" while at about the same time **Claudius Ptolemy** observed that a stick appears bent in water and measured, and calculated, the refractive index of water. By **1267 AD Bacon** was noting that "*Great things can be performed by refracted vision. If the letters of a book, or any minute object, be viewed* *through a lesser segment of a sphere of glass or crystal, whose plane is laid upon them, they will appear far better and larger.*

The above early observations gave rise to the idea of magnification by a single lens to aid in seeing small objects, such as Jonathan Swift's fleas. The limits of a single lens as a magnifier were soon reached. The possibility of seeing still smaller objects required a new idea. The use of more than one lens and thus of a compound microscope has been associated with Zacharias Jansen of Middelburg, Holland about 1595. Much development of optics was required to overcome the problems associated with spherical and chromatic aberrations which became more serious as magnifications became greater. It was realized that the resolving power of an optical microscope was proportional to the wavelength of the light being used and hence higher resolution could be obtained by going to shorter wavelengths. By the beginning of the 20th century the limits of microscopes using light were being reached. Further progress in seeing smaller objects would require new physics and new technologies

3. Lenses, Mirrors and Telescopes

In October 1608 Hans Lipperhey, spectacle-maker from Middelburg, Holland applied for a patent for a device for "*seeing faraway things as though nearby*". News of the telescope spread quickly and at 9pm 26 July 1609 Thomas Harriot observed the moon and made lunar sketches and thus disappeared the "*Man in the Moon*". More significantly, telescopes became the revolutionary tool of astronomy. October/November 1609 Galileo observed the moon and also discovered four satellites of Jupiter. December 1610 Harriot observed sunspots with his telescope and noted that the sun rotates.

The telescope, like the microscope, suffered from spherical and chromatic aberrations. In 1671 Isaac Newton introduced the reflecting telescope eliminating the chromatic aberrations of lenses at the price of having the aberrations of the sphericity of his mirrors. The latter aberrations were greatly reduced once it had been learnt how to convert a spherical surface into that of the paraboloid. The resolution of a telescope is proportional to the diameter of its lens or mirror and hence telescopes of ever increasing diameter were constructed. Even so it was not possible to even measure the diameter of any stars. Without new physics and new technologies progress must stop.

4. Quantum Physics and Relativity

The new physics and new technologies came from totally unexpected directions - namely quantum physics and relativity - probably the two most significant developments of the past century. They were to form the basis of the new technologies that became so apparent in the closing decade of the last century. I remarked that to increase the resolution of microscopes we need to go to shorter wavelengths. The vital new concept came in 1923 with de Broglie's postulate that particles may exhibit wave-like properties via his celebrated wavelength formula

$$\lambda = \frac{h}{mv}.$$

Indeed by 1927 Davisson, Germer and Thomson had demonstrated diffraction and interference phenomena for electrons. As a result electron microscopes of hitherto undreamt of resolution became possible. Not immediately as a long learning curve was required to make electromagnetic analogues of the glass lenses of the earlier optical microscopes. Problems of lens aberrations had to be overcome in the construction of electromagnetic lenses to control the electron beams. The electrons were accelerated making the application of relativistic kinematics essential in the design of electromagnetic lenses. Likewise developments in high vacuum technology and even superconductivity technology were required to perfect the electron microscope. Vision at the nanometre $10^{-9}m$ scale has become possible with even atoms becoming "visible". Electron beam diameters smaller than that of a hydrogen atom have recently been made allowing, for example, one to "see" single gold atoms on a carbon film and to "watch" pairs of gold atoms interacting as they approach each other.

5. Interferometry, Precision and Measurement

The closing decade of the last century saw the development of telescopes of up to 10metre diameter with the beginning of the new millennium seeing the successful construction of a quartet of 8.2metre Very Large Telescopes (VLT) at the European Southern Observatory (ESO) in Chile. The introduction of adaptive optics, computers and laser techniques has revolutionized ground base astronomy so that now The Hubble Telescope is often used for preliminary work with the ground based telescopes pursuing finer detail and exploring further into the depths of the universe. At the time of introduction of the Hubble Telescope many had felt it spelt the death knell of ground based astronomy. The new physics that was to radically change the use of the telescope in extending our knowledge of the very large started with Michelson's addition of the optical interferometer to the 100" Mt Wilson telescope. The addition of his 20foot ($\sim 6m$) gave him in 1927 measurements of the diameter of the star Betelgeuse that would have hitherto required a 6m telescope. That was the start of Very Long Baseline astronomy that was later to dominate the field of radioastronomy. Michelson's optical interferometric telescopes are really just starting with this years ESO success in interferometrically coupling, at this stage each pair of the 8.2m VLTs and shortly all four VLTs will be coupled. The current pairs of VLTs work with an effective baseline of 102m.

These telescopes are in essence time machines - the further the reach into the depths of the universe the further back in time they are looking. But telescopes cannot look as far back in time as particle accelerators!

6. Particle Accelerators as Telescopes and Time Machines

The development of particle accelerators throughout the past century have allowed physicists to probe the properties of matter at every decreasing distances, almost paradoxically, as the energy of the accelerators have greatly increased and their dimensions to tens of kilometres. In a sense they have become the ultimate high resolution microscopes of our time. At the same time they give information about processes that could only have occurred at the very earliest of times, say in the first ten millionth of a second after the Big Bang. In that sense they let us look backward in time, much further back than any optical telescope. This is seen, for example, in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven where gold atoms are stripped of all of their electrons and beams of the resultant gold nuclei are collided head-on at relativistic speeds ($\sim 99.95\%$ of the speed of light) to produce highly compressed nuclear matter where for a short instant of time the protons and neutrons "melt" to produce a Quark Gluon Plasma (QGP). The temperatures and pressures produced are more extreme than even those existing in the hottest of stars.

7. The Sizes of Things

The range of sizes of things considered in physics covers more than 60 orders of magnitude, from the very smallest string to the radius of the observable universe. Let us recall some basic units. We associate nuclei with the *fermi* with $1fm = 10^{-15}m$, atoms with the *Ångström* with $1\text{Å} = 10^{-10}m$ or in terms of much modern technology the *nanometre* with $1nm = 10^{-9}m$. Moving to the very small we have the *Planck length* with $\ell_p = (\frac{\hbar G}{c^3})^{3/2} \sim 10^{-35}m$ and to the very large the *light year* with $1ly \sim 10^{16}m$.

The smallest object conceived of in physics are *strings* of the dimension of the Planck length. Typically nuclei having A nucleons (protons and neutrons) have a nuclear radius $r \sim 1.2A^{1/3}fm$ while for atoms we have the typical atomic radii $H \sim 2.08$Å, $Ne \sim 0.51$Å and $Fr \sim 2.7$Å. Still larger we have the *Earth Radius*$\sim 6.4 \times 10^6 m$, the *Sun Radius*$\sim 7 \times 10^8 m$ and ultimately the *Observable Universe Radius*$\sim 10^{26} m$.

The range and strength of the four fundamental forces also exhibit striking differences in magnitude.

Force	Relative Strength	Range
Strong	1	$\sim 10^{-15}m$
Electromagnetic	$\frac{1}{137}$	infinite
Weak Interaction	$\sim 10^{-5}$	$10^{-17}m$
Gravitational	$\sim 6 \times 10^{-39}$	infinite

Note the difference in strength of almost 40 orders of magnitude and that the gravitational force is the weakest of all known forces and perhaps the most mysterious. Almost nothing is known about gravity at distances shorter than 200microns ($200 \times 10^{-6}m$) which is 16 orders of magnitude worse than the other fundamental forces which have been tested down to $\sim 10^{-19}m$. Gravity is also poorly tested on cosmological scales.

8. From the very small to the very LARGE

In the preceding we have considered lengths ranging from $10^{-35}m$ to $10^{26}m$. In earlier times particle physics and cosmology were seen as completely unrelated subjects of study. Likewise the various forces of nature were studied as distinct and unrelated subjects. The unification of the forces of nature started in the 19th century with Maxwell's development of electromagnetism, uniting magnetism and electricity and continued through the 20th century with the unification of electromagnetic and and weak interaction forces. The task of the complete unification of the four fundamental forces remains as a prime task of the 21st century. There are tantalising glimpses of such a theory coming from string theory. One thing is clear, it is no longer possible to consider particle physics, the physics of the very small, and cosmology, the physics of the very large, as unrelated subjects - both depend on each other. Undoubtedly much remains to be discovered. It is dangerous to predict the future, history is full of the unexpected.

At this stage I am reminded of Augustus De Morgan's extension of Jonathan Swift's poem to

Great fleas have little fleas upon their backs to bite 'em,
And little fleas have lesser fleas, and so ad infinitum.
And the great fleas themselves, in turn, have greater fleas to go on;
While these again have greater still, and greater still, and so on.
De Morgan:A Budget of Paradoxes, p. 377

9. Concluding Remarks

In the preceding I have tried to indicate the way in which the range of physics has changed over the centuries as science and technology have developed in such a way that it has become possible to explore things on both increasing and decreasing scales and to make the point that studies in both directions are essential to further progress in understanding the incredible universe that we occupy. Ultimately the small and the large become so dependent upon each other that it becomes impossible to consider one without the other. Each time we appear to have answered a question we are confronted with new questions, often of a totally unexpected nature. As Erwin Chargaff has noted *The greater the circle of our understanding becomes, the greater the circumference of surrounding ignorance.* I personally believe that many of the problems to be solved will be solved by young people and it is to them we must look and encourage. The advent of the 20th century was approached with great optimism as seen in Henry Rowland's address to the American Physical Society in 1899. Unfortunately his dream of a better 20th century was not realized. Recalling his words could we substitute the twentyfirst century for his twentieth century vision?

...where in the world is the institute of pure research in any department of science with an income of $100,000,000 per year. ... But $100,000,000 per year is but the price of an army or of a navy designed to kill other people. Just think of it, that one per cent of this sum seems to most people too great to save our children and descendants from misery and even death!

But the twentieth century is near - may we not hope for better things before its end? May we not hope to influence the public in this direction?

Henry A. Rowland *The Highest Aim of the Physicist* Presidential Address to the American Physical Society, 28 October 1899.

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