Nanotechnology and cosmology

G. C. Holt

Collegium Basilea (Institute of Advanced Study), Basel, Switzerland

1. Introduction

Many authors have noted the parallels between the small and large extremes of the universe in their quest for underlying comprehension and truth. With technology advances in both small and large scale instrumentation, these parallels continue to be explored and one might be tempted to posit some fundamental connexion between both instrument development and the nature of the universe.

The search for the General Unified Theory (GUT) has been the Holy Grail for mathematical physicists since Einstein failed to unite General Relativity and Quantum Theory in the 1950s. Today, eleven dimensional space-time seems to offer a degree of unification but this presents problems of comprehension in everyday life where three spatial dimensions and time in a single direction are adequate to describe and understand reality for over ninety percent of human endeavour. In fact the extra dimensions are required to represent the small scale quantum effects, which itself implies a certain circularity to the large and small dichotomy.

This paper is not GUT nor indeed a pointer to it, but merely a review, an observation of the latest technology observation tools, which measure in an attempt to understand the extremes of the universe.

2. The small and the large

Man has developed mathematics as a means of understanding nature by prediction in order to test against measured reality. The logic of man-made mathematics naturally places man at the centre of the numbering system and, like the early pre-Copernican view of the earth as the centre of the universe, may be inappropriate. However, the numbering system provides a measure of the objects of the universe, albeit relative to human comprehension. The actual values, say 42[1], have no meaningful significance although some authors might whimsically think they should have.

[1] Douglas Adams, *The Hitch Hikers Guide to the Galaxy*.

Nanotechnology Perceptions **1** (2005) 24–30
Received 23 December 2004

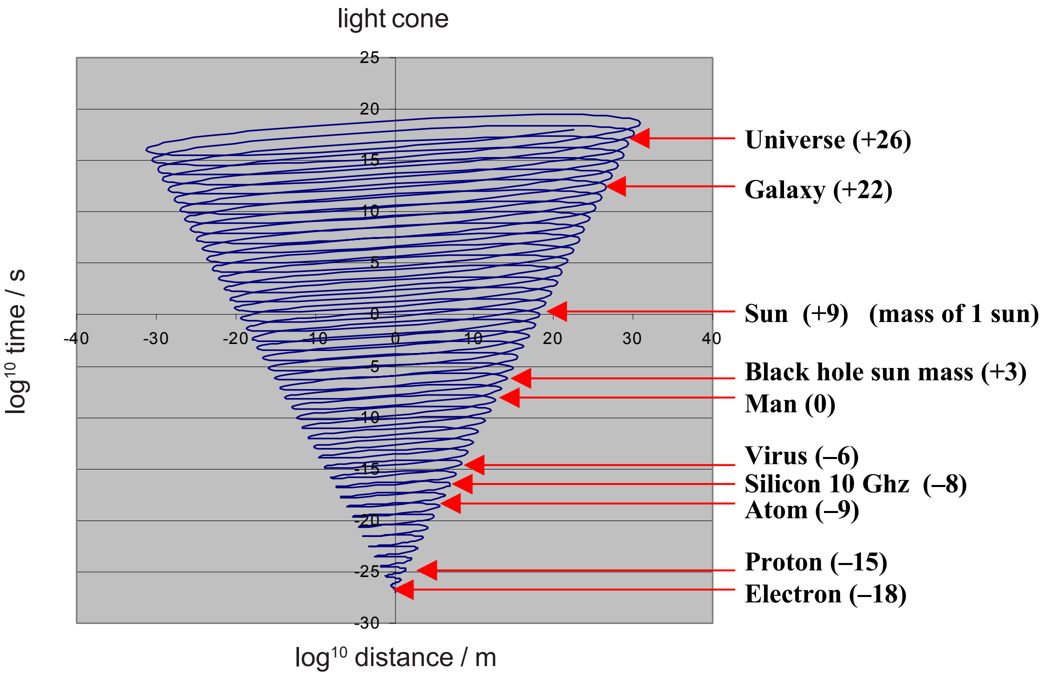

Figure 1. Objects in the universe (diameters, in parenthens, given as powers of ten of metres).

Three measures dominate our everyday four dimensional world expressed in a base ten numbering system: distance, time and energy. Through general relativity and thermodynamics, energy is equivalent to both mass and temperature while time and distance are inextricably linked by the invariant speed of light. Most objects never realize their equivalent mass as energy but exhibit a small fraction of it as temperature. It is interesting to note that only large cosmological objects like suns, neutron stars and black holes, and elementary particles at the subnanoscale level like electrons, protons and neutrons exhibit this mass energy conversion to any significant degree. A standard set of units will be used to ease comprehension of the extremes namely:

Distance in metres (m)
Time in seconds (s)
Energy in mega electron volts (MeV)
Mass in kilograms (kg).

Man occupies the logarithmic centre of the measurement scale encompassing the smallest and largest entities in the universe, and both the small and large will be explored outwards from this centre. This is perhaps a false analogy since the small spirals to an infinitesimal point (quarks and the beginning of the universe) while the large spirals to a possibly infinite volume (the expanding universe).

Table 1 shows the numbers involved. Emphasis here is on the nanoscale (10^{-6} to 10^{-9} m), which is matched by the gigascale in the large.

Table 1. Characteristic parameters of objects in the universe.

	mass /kg	mass /MeV	diameter /m	wave length /m	photon traversal time/s	instrument	resolution/m
UV photon	0.0×10^{0}	1.9×10^{-6}		1.0×10^{-7}			
X-ray photon	0.0×10^{0}	1.9×10^{-1}		1.0×10^{-12}			
electron	1.0×10^{-30}	5.5×10^{-1}	1.0×10^{-18}	3.5×10^{-13}	3.3×10^{-27}	CERN/Fermilab	1×10^{-16}
quark	6.2×10^{-28}	3.4×10^{2}		5.6×10^{-16}			
proton	1.7×10^{-27}	9.4×10^{2}	1.0×10^{-15}	2.0×10^{-16}	3.3×10^{-24}		
atom	1.0×10^{-23}	5.5×10^{6}	1.0×10^{-9}		3.3×10^{-18}	XRD	1×10^{-12}
						STM	1×10^{-10}
silicon 10 Ghz			1.0×10^{-8}		3.3×10^{-17}	AFM	1×10^{-9}
						OWLS	1×10^{-8}
virus			1.0×10^{-6}		3.3×10^{-15}	SEM	1×10^{-8}
						Microscope	1×10^{-7}
man	1.0×10^{2}	5.5×10^{31}	2.0×10^{0}				
black hole (mass of sun)	1.0×10^{30}	5.5×10^{59}	1.0×10^{3}		3.3×10^{-6}		
earth	1.0×10^{25}	5.5×10^{54}	1.0×10^{7}		3.3×10^{-2}		
sun	1.0×10^{30}	5.5×10^{59}	1.0×10^{9}		3.3×10^{0}		
galaxy	1.0×10^{42}	5.5×10^{71}	1.0×10^{22}		3.3×10^{13}	Earth telescope	
universe	1.0×10^{52}	5.5×10^{81}	1.0×10^{26}		3.3×10^{17}	Hubble telescope	

Abbreviations: XRD: X-ray diffractometer; STM: scanning tunnelling microscope; AFM: atomic force microscope; OWLS: optical waveguide lightmode spectrophotometer; SEM: scanning electron microscope.

At this small scale, the diameter is not actually observable but inferred. For instance, the electron falls under quantum theory rules and thus the Heisenberg uncertainty principle applies so that, given the momentum of the electron, the apparent wavelength is derived. This provides a minimum size and the diameter is an estimate based upon electron collision properties.

Time is effectively measured in light-seconds since it is the time taken to traverse the object by a photon in vacuum.

Quantum effects really begin at the timescale of 10^{-22} s, but electron interactions such as tunnelling occur at the atomic level four orders of magnitude longer. This means that the 10 nm thick silicon that is to be used for the next generation of personal computers will have to deal with current leakage due to the onset of quantum tunnelling.

At the cosmological extreme, distance is inferred by spectral analysis. The Hubble constant for the expansion rate of the universe and the observed red shift in the resonant frequency of excitation of known atoms provides the link between measurement and distance.

It is interesting to note that there are indeed links between the extremes, like wormholes or perhaps strings connecting massive cosmological objects to the tiniest particles. Within black holes, the tidal forces are immense and nuclear structure breaks down. The ratio of gravitational to electromagnetic force between two electrons is 10^{42}. Near the black hole singularity, a quantum foam exists where particles appear and then evaporate as energy or vice versa according to the rules of probability. These events are hidden from view by the event horizon of the black hole but to describe them requires the eleven dimensional string theory mentioned above. Until recently, these strings of energy were also thought to be invisible due to their size. However, there is a suggestion that they have been sighted near some distant massive objects[2].

3. Observation techniques

The measurement of the smallest objects is made by observing the trajectories of the fragments from collisions. The accelerators at CERN and Fermilab both use accelerator rings to make electron family particles or proton family particles, intersecting at nearly the speed of light, collide. Energies of greater than 10^9 MeV are required to break up these particles, which then produce quarks and other more massive and exotic particles. The Heisenberg principle ensures that these massive and thus highly energetic particles are short-lived and therefore rarely seen.

Moving to larger objects, observation by photon interaction becomes possible. X-rays are energetic and may change the structure of molecules as collisions with the electron shell of the atoms causes absorption of the X-ray energy and potentially the breaking of chemical bonds. However, X-ray diffraction gives resolution to nearly one hundredth of an Ångstrom (1 Ångstrom is 10^{-10} m), or that is one thousandth of a nanometre. The technique gives a diffracted shadow image of the illuminated object, which enables the atomic structure of atoms in a molecule to be determined from diffraction theory.

[2] New Scientist, 18 December 2004, issue 2478.

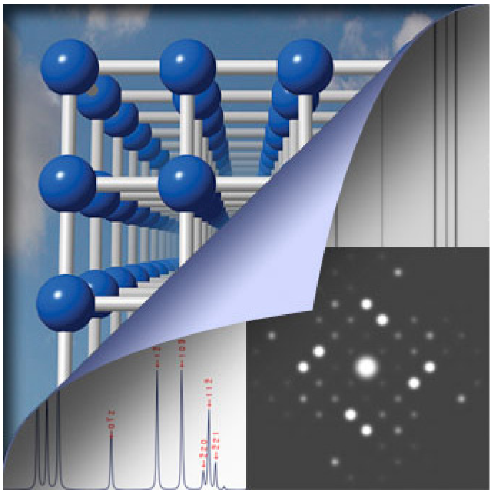

Figure 2. X-ray diffraction showing the underlying lattice structure.

The shape of molecular sized objects may be observed using the scanning electron microscope (SEM). Designed in 1942, it relies upon the electrons reflected off an object to generate an image by amplifying the received charge. Resolution to a few nanometres is achieved but the surface to be viewed must reflect electrons and thus, for non-metals, requires the object to be coated with a thin sputtered layer of gold.

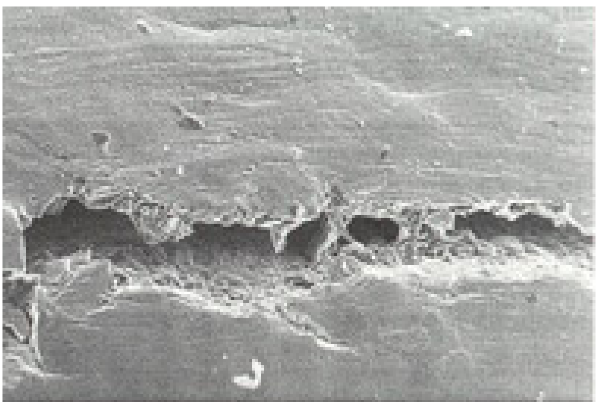

Figure 3. SEM of the surface of aluminium.

In the late 1980s, both the scanning tunnelling microscope (STM) and the atomic force microscope (AFM) were invented. These two instruments particularly have been responsible for opening up the nanometre world.

The STM utilizes the tunnelling current between two conducting or semiconducting atoms. This current increases exponentially as the distance between atoms decreases and thus provides a measure of the surface topology as the scanning tip passes over the object of interest. Resolution is determined by the characteristic distance of the quantum effect which is a few Ångstroms (a few tenths of a nanometre). The limitation of this instrument is that the object under investigation must have semiconducting properties, although recently organic material has been imaged by placing it upon a conducting substrate. The interaction between substrate and object is not fully understood but it is postulated that the substrate captures by adsorption some of the object's molecules allowing the resulting electron distribution to be sensed by the STM.

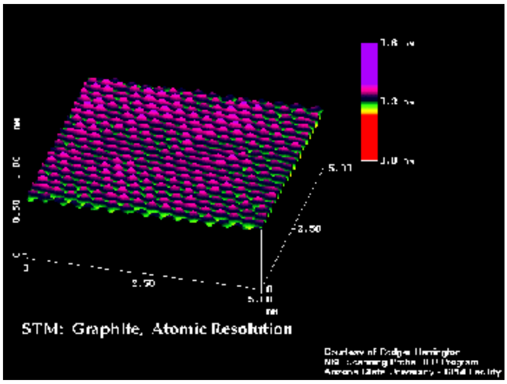

Figure 4. STM of graphite.

The AFM is a touch sensor. A fine tip is moved across the object of interest and a laser range finder measures the movement of the tip. Resolution is constrained by the tip size which is typically a few nanometres.

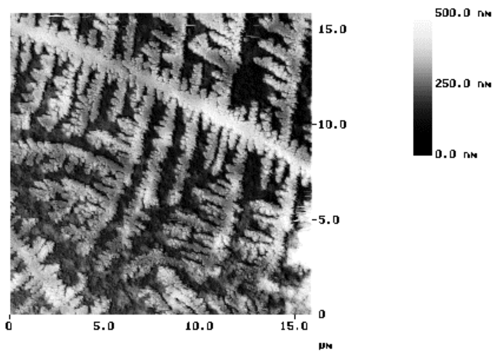

Figure 5. AFM of salt crystals on mica.

Continuing up the scale of object size is the optical waveguide lightmode spectrometer (OWLS) also known as a "molecular microscope. This measures the standing wave pattern generated by coherent infrared to ultraviolet light in a waveguide substrate coated with a molecular capture layer. Sample molecules are absorbed by the capture layer and change the energy of the guided mode propagating in the waveguide. Like X-ray diffraction, the object's structure has to be inferred from the geometry of the adsorbed molecules and their refractive properties. Objects of molecular size, tens of nanometres, are distinguishable.

Direct observation of small objects using conventional microscopes with visible light provides resolution to hundreds of nanometres. The limitation is collection and amplification of the received photons.

At this point in the journey towards human scale objects, it is worth noting that the observation techniques so far described are all active. The techniques rely upon transmitting either electrons or photons onto the object of interest. At the larger scale, observations are based upon passive measurements where the photons or particles are transmitted by the object itself either directly or reflected off some other radiating object.

Since Galileo invented the telescope in the 16th century, stars and planets have been observed continuously. The problem at this scale is both one of detection and resolution. Although the objects of interest are massive, their distance makes their resolution difficult, while enough photons must be collected to detect their radiation above that of the background. Larger and larger lenses and mirrors have enabled the furthest reaches of the universe to be observed. In 1990, the Hubble Space Telescope (HST) was launched into earth orbit. By avoiding the refractive effects of the earth's atmosphere and its light pollution, the background level is much reduced. HST is thus able to detect individual photons from objects in dark areas of the sky since it operates in the infrared to ultraviolet spectrum away from the background microwave radiation left over from the big bang.

Resolution has most effectively been tackled by utilizing the radio frequency to X-ray frequency of the spectrum in interferometer techniques. The Very Long Baseline array connecting radio telescopes at Arecibo, Jodrell Bank, Algonquin and Parkes has enabled neutron stars and black holes in the centres of galaxies to be revealed.

4. Connexions

Is there a connexion between the small and large? There obviously is in the sense that the large is made up of many of the small, but are there lessons to be learned from the observation techniques employed in the understanding of the extremes? Certainly the last decade has seen almost incredible advances in nanotechnology driven mainly by the electronics industry and its desire to feed a voracious information technology market with faster and faster processors. At the large scale, the Hubble Space Telescope has provided a similar leap forward in knowledge: observation of light from the edge of the universe and the possible observation of a naked string.

The link is probably the processors which have allowed instrument control and image enhancement, and man's insatiable quest for knowledge. The ability to perform more and faster calculations has enabled instruments like the HST, AFM and STM to provide meaningful images. Advances in image processing developed for space observation and travel have been transferred to the small scale and now provide the pictures with nanometre resolution we have become accustomed to.

The challenges for the future are perhaps to be found in filling in the gaps between contemporary instrumentation. For instance, the subnanometre scale is difficult to image, except by X-rays where the underlying shape is calculated (inferred) rather than 'seen'.