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The Enigma of the Microworld.

As we observe nature around ourselves we learn about its behaviour, or some of it instinctively, some of it more explicitly, through sense ~~experiences~~ perceptions.

Thus there are a variety of experiences relating to the motion of bodies, what in scientific parlance we call the physical systems: The motion of objects on the ground, falling of bodies from above: (Newton's apple), rain drops, stone thrown upwards.

Then there are experiences of day and night involving the presence or absence of light; Of lights of various colours and brightness; Of sounds of various pitches and intensity. And we have the experience of phenomena involving both light and sound: the lightening and thunder. And it was Benjamin Franklin who found that "electricity" also played a role in the lightening phenomena, while ~~Faraday~~ Ampère showed that moving electricity produces magnetic field.

There are of course, complex phenomena, which involve the motion of objects such as flight of birds, aeroplanes etc which are not simple motion of bodies, but autodriven ~~ma~~ and navigated motions. We shall not address such systems and phenomina.

~~In each of the phenomena method mentioned above~~

As we accumulate experience about the world around us we develop instincts and intution about them. Thus if ~~so~~ we see someone throws a stone at us we instinctively duck or move in a direction so as to avoid it. Thus from the multitude of experiences involving the throwing of stones at various angles and initial speed as gauged by the ~~motio~~ movement of the thrower, we develop reactions in response to them ~~accd~~ accordingly and in some sense learn about the various possible trajectories of the stone

There could be no better example of this than the game of cricket where the battle of wits between the bowler and the batman involving essentially the trajectories of the

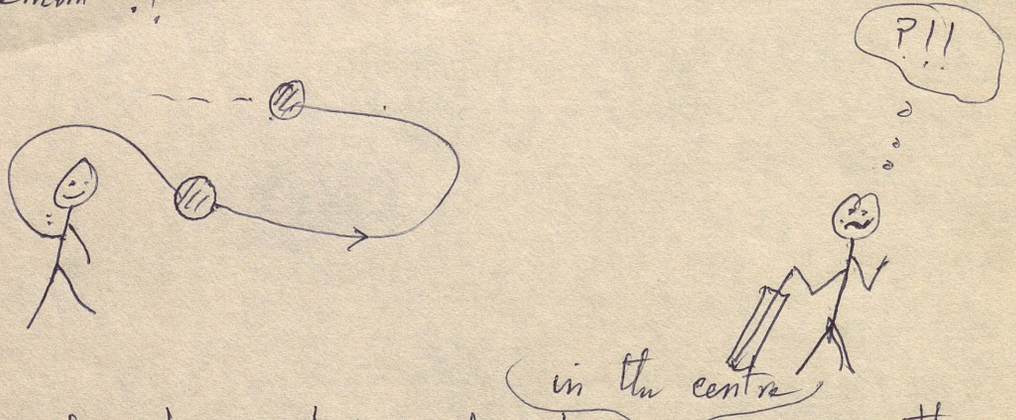
cricket ball, makes the game of cricket, the delight that it is: the inswinger and the outswinger of the medium pacer; the off break, the leg break and the googlie of the spinners! And the trick lies in how a bowler can camouflage his actions and produce a surprise for the batsman, who must constantly try to expose the bowler and the battle goes on..

The game of cricket in a sense exemplifies the battle ~~between~~, if one can call it so, between the scientist and nature, which I shall elaborate shortly

~~The point of the above example is that if a~~

Inspite of this battle of wits between the bowler and the batman, the fact, however, remains that a good batsman develops a fair understanding of the motion of the ball and ~~an expec~~ ~~a good~~ can, in most cases, guess read rather well where the ball would pitch: that is he can guess rather well the expected trajectory of the ball. ~~without ever having solved a differential~~ In other words, barring minor

though important variations, there are no surprises in the motion. For instance, it will not be expected that while throwing the ball forward, it actually curls up and reverses the direction of movement !!



Or the ball hits the bat and goes through it, ~~and~~ hitting the wicket without damaging the bat !! That would be the real surprise for the batman !! And I guess he would flee the field if he has to face such ~~a bowler~~ a balls. The game of cricket will then be finished.

The game of cricket is in a sense, exemplifies the 'battle' if you like, between nature and the scientist. with nature like a bowler bowling bouncers and googlies at the scientist and worse. And the worse they are, the more the scientist enjoys them.

One such "bouncer" was presented by nature in the form of a puzzle of the planetary motion. Tycho Brahe had tabulated the motions of the planets by through painstaking observations.

But nobody knew what, if any, were the systematics of the planetary motions. Were there any common "Laws" governing the motion?

This problem was taken up by Johannes Kepler to understand*, in the same spirit as a batman to observe understand the bowling pattern of various bowlers to extras and learns about the behaviour of the moving ball as bowled by a bowler.

After working unceasingly for 16 long years Kepler was finally able to conclude that determine the laws of planetary motions referred to the Kepler Laws.

I
II
III

* find out pattern in planetary motion

After working unceasingly for 16 long years, Kepler was finally able to extract patterns of ~~m~~ ~~planetary~~ ~~motion~~ behaviour in the ~~plane~~ motion of planets, but ~~more~~ in quantitative terms. These are ~~enshired~~ (enshrined) in what are known as "Kepler's laws"

I. ~~Motions~~ Planetary orbits ~~as~~ are ellipses with sun as one of the foci.

II. Equal areas are swept in equal times

III R^3/T^2 = constant for all planets

~~All~~ ~~as~~ ~~As we have studied~~ ~~It was~~ Subsequently, Newton gave his equations of motion and postulating an inverse square law of force between the gravitating bodies

$$m\frac{d^2\underset{\sim}{r}}{dt} = G\frac{Mm}{r^2}\hat{\underset{\sim}{r}}$$

he was able to ~~derive~~ obtain Kepler's law as ~~a~~ solution of the equation of motion.

~~We~~ This was the single most important development

in the annals of scientific discoveries, ~~for~~ because, ~~it~~ for the first time, we were able to ~~extract~~ synthesize all the ~~experiments~~ observational information as compiled painstakingly by Tycho Brahe, and extracted by Kepler in the form of Kepler laws, in the form of a mathematical equation. The different planetary motions and indeed of all ~~the~~ the bodies of the solar systems, ~~the~~ including the comets ~~and moons~~ and meteorites then follow from the equation of motion ~~but~~ with ~~and~~ different initial conditions.

~~Then~~ This equation of motion - initial value paradigm then formed the basis of understanding the motion of bodies in nature, and also of fluids and gases and molecules thereof. This ~~held the s~~ paradigm held the scene for ~~4 cen~~ four centuries as its ~~domain~~ ~~was~~ validity was ~~a~~ ~~teste tried and tested extended~~ tried, ~~an~~ tested and extended to larger and larger domains. ~~This led to the development of an intuition~~ As one has studied ~~motions~~ a variety of motion using this paradigm, one is led to the development of an intuition about the behaviour of the motion which is based on this paradigm.

Nuclear model of the atom and application of Newton's laws:

When the Newtons laws were applied to the motion of electron ~~in an atom~~ around the nucleus in an atom, they failed. ~~They~~ One to explain the spectral lines which the one was supposed to explain.

This then constituted the first example of the departure from ~~Now~~ the Newton equation - initial value paradigm of classical mechanics - ~~The first case of the Enigma of the Microworld~~. as applied to the or ~~Microworld~~ Microworld of the atom. ~~The intuitive~~

We know that a beginning to understand the atom was made by Bohr (1913) through an ad-hoc model - the Bohr atom. It was still, however, based on some ~~had some elements of~~ and properties of classical mechanics, namely the existence of Poincare invariant. ~~and~~ Bohr postulated that only certain orbits were allowed orbits, namely those for which

$$\oint p\,dq = 2\pi n\hbar.$$

This was able to explain the observed spectrum of hydrogen atom.

Then 1923 de Broglie made a most spectacular suggestion leading to the prediction that a particle with a momentum $p = mv$, behaves as a "wave" of length λ

$$\lambda = h/mv \quad , \quad h = \text{Planck's constant}.$$

Electrons moving with a certain velocity v were expected to exhibit wave like manifestation such as interference and diffraction phenomena.

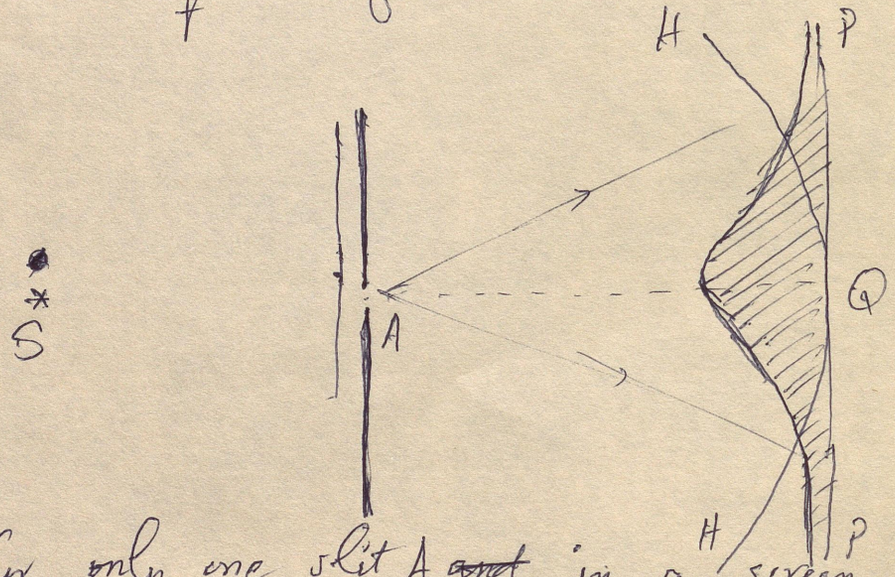
This was the first real enigma that a particle such as an electron belonging to the "microworld" presented:

We had been taught to consider an electron as a particle of concentrated charge e and concentrated mass m and yet if it were to behave as a wave it requires from our intuition about wave motion that it ought to be an extended object.

The most surprisingly the interference and diffraction phenomena, that was predicted for the electrons by de Broglie was indeed found to be experimentally verified by Davisson and Germer in the U.S.A and G.P. Thomson in the U.K

Davisson and Germer found it in fact, rather serendipitously as they were carrying out experiments to study the scattering of electrons by nickel crystal

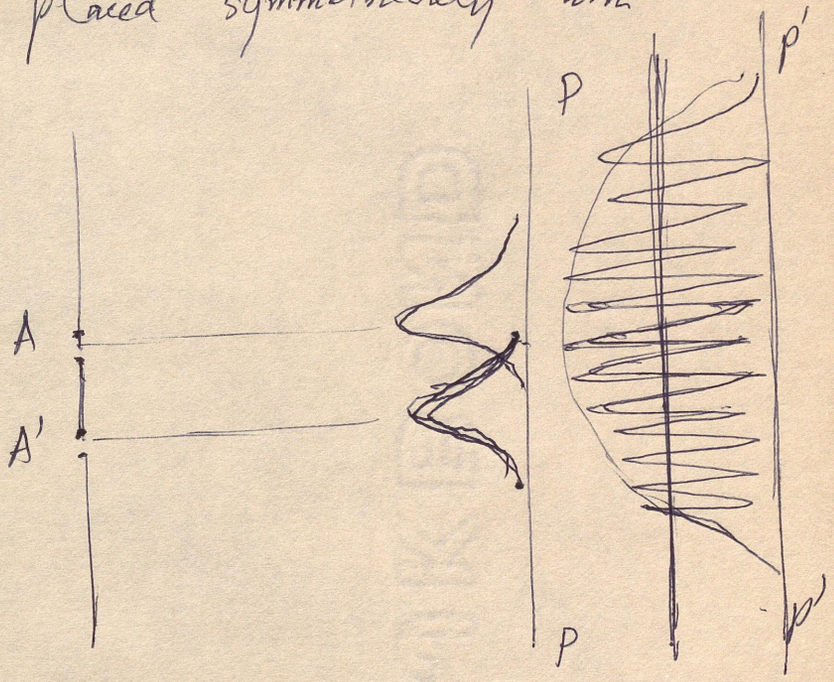
To appreciate the enigmatic nature of the wave behaviour of electrons it is interesting to examine the interference of electrons in a double slit experiment



First, consider only one slit A in a screen and an electrons source S and a plate PP to record the arrival of the electrons. If we were to have a spherical plate with AQ as a radius then the distribution of the arriving electrons would be uniform over it. But projected on a plane plate PQP, it will exhibit a one-humped distribution as shown centred around the point Q, which is directly opposite to the slit

~~physically~~ intuitively
This behaviour is ~~understandable~~
acceptable and to some extent also understandable.

Consider now two slits in the screen with the same source S placed symmetrically with respect to the slits



If one uses the same pattern of behaviour, with respect to each slit as one ~~does~~ saw in the case of the single slit then ~~we~~ s we should get a double humped ~~bell~~ distribution as shown on the plate PP in the figure. But according to the wave ~~notion~~ theory ~~the~~ pattern ~~predicted~~ one should get the interference pattern as shown ~~in~~ on the plate P'P'. This is in radical departure ~~of the~~ as from a behaviour as expected according to the ~~intuitive picture~~ ~~bell~~ particle nature of the electron

Furthermore, being a particle, an electron has to pass through either the slit A or slit A', but not through both (as the electron is going through a particular slit)

This means that the mere presence of the second slit leads to the change of pattern (and therefore the position at which the electron ends up on the screen), ~~while the electron~~

This is certainly bizarre and certainly contrary to ~~anything that one has examined before regarding the behaviour of electrons as particles~~. what one expect on the basis of Newton's equation of motion. But such an interference pattern has actually been observed, in a double slit experiment recently

This then is the ~~real~~ enigma relating to the behaviour of electrons in micro-dimension of the micro-world.

The Aharonov-Bohm effect

There is another interesting effect associated with the above double slit experiment. This has to do with the appearance of the magnetic vector potential $\underset{\sim}{A}$ in the Schrödinger equation:

$$\frac{1}{2m}\left(\frac{\hbar}{i}\nabla - e\frac{\underset{\sim}{A}}{c}\right)^2\psi = E\psi.$$

According to the classical Lorentz eqn. of motion, it is the

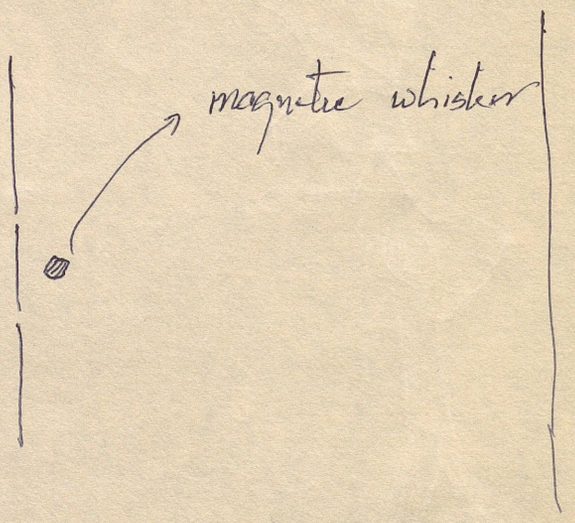
$$m\dot{\underset{\sim}{v}} = \frac{e}{c}\underset{\sim}{v}\times\underset{\sim}{B},$$

it is the magnetic field $\underset{\sim}{B}$ which is an observable, that is what affects the motion of a charged particle. But the Schrödinger equation involves the vector potential $\underset{\sim}{A}$ rather than the magnetic field; so this should have some observable consequences in quantum mechanics.

Indeed, it was argued by Aharonov and Bohm in 1959 that $\underset{\sim}{A}$ does have an observable consequence, which was verified experimentally

Consider a long solenoid of small cross section placed in front of the double slit (or alternately a long magnetic whisker)

The magnetic field is



completely confined within the internal domain of this whisker while it is zero outside if (ideally) the whisker is infinitely long. But in the domain outside there is non-zero curl-free magnetic potential A. Thus as the electron pass from the source across the double slit to the screen through the space around the whisker, they 'see' the vector potential A, but no magnetic field.

Classical mechanically the electrons should not be affected but it is found that they are affected: One finds that the entire interference pattern is shifted by an amount proportional to the magnetic flux

enclosed in the whisker.

This is of course another surprise of the microworld. There are innumerable cases of such enigmas. But I shall deal with ~~two more~~ one more (~~or two, if time permits~~).

Einstein-Podolsky-Rosen problem

As is so well known, Einstein was not completely happy with the interpretation of quantum mechanics. In particular, he was firmly of the view that since it involved probabilistic concepts and an event could be described only probabilistically in quantum mechanics, it could not be a complete description of nature. To try to prove its incompleteness he designed the following



When one looks at ~~a night~~ the sky on a clear cloudless night one cannot fail to be struck by its breathtaking beauty and splendour. And it's must have been even more beautiful before our "progress" and "advances" polluted our atmosphere.

But it is not just the spatial dimension of our universe that the night sky so spectacularly exhibits, but it also reveals the time-dimension through the motion of some of the objects against the background of others. The observers of the night sky since time immemorial have ~~savoured the fascination of~~ been enchanted and fascinated by the phenomena of motion in the sky observed through the light emitted by the moving objects.

~~It is these motions which~~

The early observers all over the world, the Mesopotamians the Hindus and the Chinese did recognise the regularities in the motion of certain objects in the night sky which we now know to be the "planets." They also recognized the importance of 'positions' in the sky in the ~~astrisms~~ ag: in the form of "asterisms"

Laws of Mechanics

– a Quest for Harmony

Positions of the planets in the sky were specified with respect to the various 12 asterisms which the Hindus had also considered in ~~28~~ 27 "Nakshatras".

While the motions were qualitatively studied by the Hindus and the Chinese; however, it was not until Tycho Brahe the ~~Danish~~ Danish astronomer that they were studied systematically and quantitatively, and tabulated, ~~in~~ precisely. Johannes Kepler (b. 1571) the ~~Austrian~~ German astronomer (d. 1601) who came to work with Tycho Brahe had great faith in the quality of observations of Brahe, which was to an important role in the formulation of the laws of motion which go by his name — the Kepler laws. (Kepler died Nov 15, 1630)

~~Almost~~ Contemporaneously with Kepler Galileo Galilee (d. 1642) was carrying out experiments in the "terra firma" which were on the terrestrial laboratory which were to lay the foundations of the laws of motion as we know them today.

For ~~twelve~~ sixteen long years, Kepler struggled to fit Tycho Brahe's observations into a scheme which would satisfy his quest for order in nature using circles within circles and all other possible combinations, but to no avail. His full and total faith in the Brahe observations in the end prevailed upon his own prejudices in favor of particular models, and objectivity triumphed over subjectivity.* Finally, when he finished writing the book containing the results of his findings, his ecstasy knew no bounds and he declared "When sixteen years ago I urged as a thing to be sought - that for which I joined Tycho Brahe .... at last I have brought to light and I recognize its truth beyond my fondest expectations .... The die is cast, the book is written, to be read either now or by posterity, I care not which, - it may well wait a century for a reader, as God has waited six thousand years for an observer."

* and the Kepler laws flowed out of the observations of Tycho Brahe as they should have.

The "book" did not have to wait for a century, and indeed constituted the starting point for the scientific revolution that we witnessed in the succeeding centuries. The first and foremost, the Kepler laws constituted a triumph for the Copernican system and thus provided a concerning and desirable change in our perception and perspective from the self-centred world to the extra-centred one. This view, much against the church doctrine, was to play a crucial role later in our quest for knowledge of the Universe around us.

Contemporaneously with Kepler (b. 1571 - d. 1630) Galileo Galilei (1564–1642) was carrying out experiments in the terrestrial laboratory which were to lay the foundations for the laws of motion as we know them today. Galileo is credited with the "law of inertia" which is the cornerstone of the laws of motion. This law was deduced essentially from idealization based on day to day observations and explicitly also, I suppose, by carrying out explicit experiments

→ With this the earth dissolved its identity and joined as a member of the solar-system family, though a unique member indeed — all for the sake of harmony!

Did these terrestrial observations ~~law~~ on motion ~~and~~ have anything to do with the motions of planets ~~? In particular~~ in the heavens ? In particular, would the laws of motion as deduced through experiments on terrestrial objects apply equally well to the motion of the heavenly objects ? And could Kepler's laws on planetary motion be related to and understood in terms of the laws of motion as deduced ~~from~~ by studying terrestrial motions ?

This was a very important question in the history of scientific evolution ? Was it sought to, for the first time, to extend the territories of a law to other domains. From terrestrial to extra-terrestrial and vice-versa. The answer to it was provided in the affirmative by Isaac Newton (1642 - 1727) who was born the year Galileo died, and in a sense continued and completed the task which Galileo started. ~~and~~ He also thereby met the challenge of understanding the laws that Kepler left behind. ⟶

With Isaac Newton thus born was not only ~~born~~ the science of mechanics, but also the science

* the unwilling Mr Newton did.

→ Cajoled and persuaded by Halley to apply his "laws of motion" which he had not published, to the motion of the Comet (Halley which Halley had observed) * he was able to explain all the previous recorded sightings of the comet and predict its next appearance.

It was for the first time that a prediction was made and subsequently verified. It was a triumph of the methods of science, of the method of theoretical physics. More importantly however, it established the principle of the "universality of the laws of motion". This principle of universality of the physical laws was later to be extended to the other laws of physics without hesitation..

of theoretical physics. While Galileo ~~ought~~ is regarded as founder of the "experimental science", Newton is truly the founder of theoretical physics.

This inter relationship between the motions on earth and motions in the heavens through the universal laws governing them thus constitutes the first example of a ~~the title of the~~ quest ~~(title)~~ for harmony between the earth and the Universe around us.

~~Laws of~~ Electromagnetism - a quest for partners

The ~~later~~ next century witnessed the reformulation of the laws of mechanics at the hands of Lagrange, Hamilton and Gauss no new advances were made in the discovery of physical laws. It was only with Cavendish and Coulomb in the late part of the 18th Century that the presence of electrical ~~forces~~ charges and forces between them ~~were~~ ~~found~~ discovered. This was followed by ~~the~~ the discovery ~~the~~ of electrical current by Volta and discovery of the magnetic effects of ~~the~~ currents by Ampere.

But ~~the most important discovery of~~ it was (1791-1867) Michael Faraday ~~who~~ who made the most pioneering discovery ~~of the time~~ which showed that there existed a relationship, ~~between~~ a partnership between

Your life is a world-line joining a series of bifurcation ~~points~~ or multifurcation points with the connecting segments representing the choices that you have made at each of these points. The success you have in life is no small measure determined by the choices you have made, but more importantly on how ~~well and~~ positively and single-mindedly you have performed after you have made the choice, right or wrong!

electricity and magnetism: that a time rate of change of magnetic field leads to the generation of an electrical field of the induction type. This pointed towards a synthesis of the apparently different ~~two~~ physical ~~eff~~ ~~properties~~, ~~x~~ phenomena, namely electricity and magnetism. The process ~~was as we know~~, of the synthesis of the two disciplines was, as we know, completed by Maxwell by introduction of the displacement current.

The resulting laws of electromagnetism which incorporate the Coulomb law (of inverse square force) in the Poisson eqn., the Faraday law of induction, and the Ampere law supplemented by the displacement current $\partial \underset{\sim}{D}/\partial t$ are now referred to as the Maxwell's equation

Maxwell's Equations

$$\begin{cases} \text{curl } \underset{\sim}{B} = \frac{4\pi}{c} \underset{\sim}{J} + \frac{1}{c}\frac{\partial \underset{\sim}{D}}{\partial t} & \text{[Ampere's law with Maxwell's displacement} \\ \text{div } \underset{\sim}{E} = 4\pi \rho & \text{— Coulomb law} \\ \text{curl } \underset{\sim}{E} = -\frac{1}{c}\frac{\partial \underset{\sim}{B}}{\partial t} & \text{— ~~Ampere's~~ Faraday law} \\ \text{div } \underset{\sim}{B} = 0 & \text{— No magnetic monopole} \end{cases}$$

The last equation merely expresses the empirical fact that no magnetic monopoles have so

for been found.

Needless to say the electromagnetic theory as embodied by Maxwell's equations has unified not only electricity and magnetism, but the entire spectrum of entities namely light, ~~heat radiation~~, various colours heat radiation and X-rays that we have been so familiar with.

Once again it is the synthesis of the various phenomena through the ~~universality~~ of the new laws formed to be governing them which has played an important role in our understanding

Once again the laws enunciated and new equations postulated about electromagnetism have brought about an unprecedented Synthesis of a variety of diverse phenomena which were apparently unrelated to each other. It was again a landmark of a magnitude compared to that of the discovery of mechanics as embodied in Newton's laws of motion. Once again we had mathematical equations which not only synthesized but also gave us the power to predict make predictions about new phenomena ~~that since the light and~~ in general the electromagnetic wave spectrum is related to electromagnetism ~~then~~

Thema

~~received from the stars and the planets it~~ ~~provided us a basis to make inquiries about what may be happening up there~~

If one were now to use the principle of the universality of these laws and extend their applicability to extra-terrestrial domains, then these laws ~~provide~~ of electromagnetism and the Maxwell equations would provide us means to study the electromagnetic phenomena in these extra-terrestrial domains and to ~~attempt to~~ understand various processes in terms of these laws.

The Atomic Quest - Journey into the microcosm.

While astronomers did continue to look at the heavens through their telescopes and making spectroscopic observations, there were no major ~~for~~ advances in our frontiers of astronomy. The focus of attention through the ~~nineteenth~~ 19th century was the thermodynamic behaviour and the constitution of matter. ~~The scientists were now~~ who were the chemists of the 18th and 19th century were the ones mostly responsible for making advances towards our understanding of the constitution of matter. By through the work of John Dalton

Avogadro and others. By the end of the 19th century the atomic theory of matter was firmly established and though there were still some diehards who refused to do so.

What was an atom made of? This was now the question which occupied the minds of the physicists. Following the discovery of electron by J.J Thomson, Kelvin proposed in 1902 an electrical model of the atom, where the positive charge was distributed uniformly and electron were embedded in it like "raisins-in-bread". But it could not last.

The Rutherford atom

Can a solar system like structure exist at the micro-scale? Or say in the context of the structure of the atom? I do not know whether Rutherford actually did ask such a question in his quest for the structure of the atom when he performed his experiment on the scattering of α-particle by solid targets But

to the above question
the answer that he or got from his experiments gave was an the affirmative.

Thus for the first time a model of a system (the solar system) – the Copernican model – found in the macrocosm, found an image in the microcosm separated in dimensions by an order 10^{23} (taking the dimension of solar system ~ 100 AU and atomic dimension ~ 1 Å = 10^{-8} cm). An atom was found essentially to be a solar system in the microcosm.

This also led, to the realization that there are two widely different interactions in nature: the gravitational interaction and the electromagnetic interactions. The relative strength is essentially given by $e^2/Gm^2 \simeq 10^{43}$. (This power is almost double what separates the microcosm from the macrocosm at the solar system dimensions)

The two features pointed about above, namely (i) the application of concepts of microcosm to macrocosm and vice versa and (ii) secondly (ii) comparison of the strengths of interaction occur again and again

history of
in the evolution of microcosm and macrocosm.

Lord Kelvin's two dark clouds:

Towards the turn of the last century Lord Kelvin ~~was so satisfied~~ seemed rather satisfied with the state of understanding of the physical world. Yet he was a little concerned and he referred to the existence of "two dark clouds" on the horizons of physics. These were

(i) The ultra-violet catastrophe of the Rayleigh-Jean law

and (ii) the negative result of the Michelson-Morley experiment.

As it turned out, these really were the "dark-clouds". Because, out of them came two new horizons which ~~revolutionized the physics~~ constituted the cornerstones of the revolution in physics in the twentieth century.

The resolution of the ultraviolet catastrophe culminated in the birth of the "quantum" leading to the quantum revolution

While the negative result of the Michelson-Morley experiment ~~that~~ was resolved in terms of

"Special an unknown clerk in the patent office in 1905 in the theory of relativity" enunciated by Einstein. It must however be stated that at Einstein was the M-M experiment was not the motivation for Einstein's relativity. In fact, Einstein was not probably aware of the result of the M-M experiment.

The two new horizons that were so discovered it ought to be noted dominated the evolution of the Microcosm and the Macrocosm

Between 1910 and 1915, Einstein developed what he termed as the "General Theory of Relativity" which was essentially a theory of Gravitation. It was a result of not motivated by any known experimental fact except perhaps the empirical law determined discovered by Galileo almost four hundred years ago, namely the equivalent "principle of equivalence" The whole structure of the theory is then built over this single innocent looking principle [namely "all bodies regardless fall under a gravitational field with an accelera the same acceleration independent of their masses" (This is indeed what Galileo found from the Tower of Pisa)] using pure reasoning.

In Weyl's words:

"It is the greatest example of the power of speculative thought"

and he continued elsewhere

"It is as if a wall which separated us from truth has collapsed. Wider expanses and greater depths are now exposed to the searching eyes of knowledge, regions of which we had not even a presentiment. It has brought us much nearer to grasping the plan that underlies all physical happening".

And Eddington in his Space, Time and Gravity (1920) wrote:

"By his theory of relativity Albert Einstein has provoked a revolution of thought in physical science"

And finally Einstein himself said of his theory

"Scarcely anyone who has fully understood this theory can escape from its magic; the theory represents a genuine triumph of the method of the absolute differential calculus of Christoffel, Ricci and Levi Civita".

The Einstein's theory of gravitation (or general relativity) is described by the following equations

$$R_{ik} - \frac{1}{2} g_{ik} R = -\frac{8\pi G}{c^4} T_{ik}$$

where $R_{ik} \equiv$ Ricci Tensor, $R \equiv$ Ricci scalar,

$g_{ik} \equiv$ space time metric $G \equiv$ gravitational const.

and $c \equiv$ speed of light.

Einstein's theory, as a theory of gravitation
theory of the Universe : the Macrocosm.

Einstein immediately realized that he could apply his theory to the Universe. He thus made three simplifying assumptions for the large scale structures in it:

(i) The Universe is homogeneous
(ii) " " is isotropic
(iii) " " is static

The Einstein equations thus provided for the first time a framework which enabled one to ask questions about the "Macrocosm" beyond the realm of pure speculation. They also enabled one to make assumptions (such as (i) (ii) & (iii) above) about the large scale structures in the Macrocosm and compare their consequences with observations

One of the Kelvins dark cloud thus led us on to the path to the Macrocosm.

Coming to Einstein's assumptions (i) & (ii), quite clearly the Universe is neither homogeneous nor isotropic on small scale. They refer to the density on a sufficiently large scale

Einstein soon found (1917) however, that no static solution of his original equations were

possible which were both homogeneous and isotropic.
He needed an extra term to add to his equations
— the Cosmological term λg_{ik} — in order to
obtain static solution. Einstein, of course, thought
that the Universe was static or time stationary.

Friedman, however, dispensing with the assumption (iii)
obtained in 1922 an expanding solution —
an expanding Universe. This was also
obtained independently by Lemaitre in 1927.

Unaware of the Friedman solution of the expanding
Universe, Hubble made in 1929 a most
epoch-making discovery when he measured the
red-shifts of distant galaxies. He found
that the larger the distance of the galaxy was
from the earth, the more was the red
shift of the light from the galaxy.
This meant that all galaxies were receding
from our galaxies in all directions. And since
our galaxy is not supposed to be
any preferred galaxy, all galaxies, it ought to be concluded,
are receding from each other.

Fig. shows the original Hubble diagram of
Red shift vs distance from which he concluded
the expansion of the Universe

Back to the Microcosm:

Perhaps, I have gotten ahead of myself in the Macrocosm, leaving behind very important developments in the realm of the "microcosm" which had in turn great impact on our understanding of and further exploration of the macrocosm.

Lord Kelvin's other 'dark cloud', namely the ultra-violet catastrophe of the Rayleigh-Jeans law gave birth to the quantum. Lummer and Pringsheim and very careful measurements by others of the Black-Body radiating spectrum had established the form of the latter. But it was not what the classical theory embodied in the Rayleigh-Jeans law gave. It agrees with the latter only in the long wave length limit.

Planck in trying to understand the form of the B-B. spectrum ~~was~~ in terms of the concepts of statistical mechanics, applied to radiation was "compelled" to introduce a concept of a "quantum of radiation" in terms of which energy was exchanged between the matter and radiation. It was an "act of desperation" on the part of Planck as he put it, (as there was no other alternative

exist in equilibrium. It has to go on contracting and contracting, radiating and radiating until it collapses to what is now referred to as a "Black Hole".

I would like to recall a rather interesting point made by Chandrasekhar ~~when~~ in a series of lectures given by him at PRL during his visit as Vikram Professor in 1982. He highlights a very important point which is the overall theme of the present talk: namely the inter-relationship between the microcosm and macrocosm.

He starts with the question

"Why are atoms as they are"?

It follows from the Bohr atomic theory that the typical dimension of the atom is given by

$$a_B = \left(\hbar^2 / 4\pi m e^2\right) \text{ - Bohr radius.}$$

This is just a combination of the natural constants.

Thus an atom is what it is because the above combination gives its correct dimensions.

Similarly, "one can ask the question", says Chandrasekhar, "Why are stars as they are"?

One can define introduce a combination of natural constants with the dimension of mass. as follows:

$$\hat{M} = \left(\frac{hc}{G}\right)^{3/2} \frac{1}{m_H^2}$$

where m_H is the mass of hydrogen atom, & G is the gravitational constant. This gives

$$\hat{M} \simeq 29\, M_\odot$$

This of course, ~~does~~ does not mean that all stars have ~~it~~ the mass $\sim 29\, M_\odot$. But it does provide a somewhat natural mass scale in terms of which the mass of a star can be expressed.

If we consider the equilibrium of a star then we see that the star is kept in equilibrium under the gravitational force of contraction on the one hand, and an outward force provided by a sum of radiation pressure and kinetic pressure

It turns out that the fractional radiation pressure ~~must~~ is greater for more massive ~~particle~~ stars, and smaller for less massive ones. Indeed the ratio (p_r/p) depends very sensitively on the mass, so that in a very narrow mass range the p_r ratio (p_r/p) changes from a very small value to almost unity. When $(p_r/p) \simeq 0.5$,

"What happens is a star".

~~This gives a the mass of a star is~~

~~Thus what determines the~~

It turns out that the magnitude of the radiation pressure is determined by the combination

$$0.2\left(\frac{hc}{G}\right)^{3/2}\frac{1}{m_H^2} \simeq .6 M_\odot$$

One can ask the question what happens to a star of a given mass

Hydrogen burning → Radiation of energy
→ Contraction

$M = 10 M_\odot$ — Radiates 10^4 times more than the Sun

Life time smaller → 10^8 years

What happens when a star loses all its energy

As the star contracts → pressure in the interior increases

~~and the temp~~

The pressure can then balance the gravitational pull with densities ~ 10^6–10^8 gms/c.c

⇓

White Dwarf star

It was shown by Chandrasekhar that if one takes relativistic effects into account, there only stars with $M < 1.4\, M_\odot$ can be in an equilibrium state of a white dwarf after exhausting their source of energy.

Again it is the same combination of physical constants which determine the limiting mass of $\sim 1.4\, M_\odot \Rightarrow$ "Chandrasekhar limit." [This assumes that electrons and ions remain in their form]

Stars with larger mass $M > 1.4\, M_\odot$ (which have exhausted their source of energy).

Can the contraction be arrested.

For larger mass and greater gravitational pressure energetically it is more favourable that electron combine with protons to give neutrons because of Pauli exclusion principle

This would lead to a "neutron star"

~~These have been~~ The "neutron stars" which were predicted to exist by Landau ~~and studied~~ in 1932 ~~and~~ 1933 soon after the discovery of Neutron by Chadwick in 1933.

Finally when $M > 2M_\odot$,

the star would continue to contract further until it becomes a "black hole"

We may now again point out the fact, that both the Chandrasekhar limit for White dwarfs and the prediction of the existence of "Neutron stars" (subsequently observed) are a consequence of the application of laws as deduced from observations in terrestrial laboratory. In particular, it is remarkable that the one principle, namely the Pauli exclusion principle which was discovered in connection with the structure of the "microcosm" plays such a crucial role in understanding the very existence of such macro-objects as the "white dwarf" and the "Neutron stars". We see here the case of the Microcosm

~~One could continue the story even further~~

helping in the quest of the Macrocosm.

When one looks at the sky on a clear cloudless night, one cannot fail to be struck by its breathtaking beauty and splendour. And it must have been even more beautiful before our "progress" and "advances" polluted our atmosphere.

But it is not just the spatial dimension of our universe that the night sky so spectacularly exhibits, but it also reveals the time - dimension through the motion of some of the objects against the background of others. The observers of the night sky since time immemorial have been enchanted and fascinated by the phenomena of motion in the sky observed through the light emitted by the moving objects.

The early observers all over the world, the Mesopotemians, the Hindus and the Chinese did recognise the regularities in the motion of certain objects in the night sky which we now know to be the "planets". They also recognized the importance of 'positions' in the sky in the form of "asterims". Positions of the planets in the sky were specified with respect to the various 12 asterims which the Hindus had also considered in 28 "Nakshatras".

While the motions were qualitatively studied by the Hindus and the Chinese; however, it was not until Tycho Brahe, the Danish astronomer, that they were studied systematically and quantitatively, and tabulated precisely. Johannes Kepler (b.1571), the German astronomer, who came to work with Tycho

Brahe, had great faith in the quality of observations of Brahe, which was to play an important role in the formulation of the laws of motion which go by his name - the Kepler laws. (Kepler died on Nov.15, 1630).

For sixteen long years, Kepler struggled to fit Tycho Brahe's observations into a scheme which would satisfy his quest for order in nature using circle within circles and all other possible combinations, but to no avail. His full and total faith in Brahe's observation in the end prevailed upon his own prejudices in favour of a particular model; and objectivity triumphed over subjectivity, and the Kepler laws flowed out of the observations of Tycho Brahe as they should have. Finally, when he finished writing the book containing the results of his findings, his ecstacy knew no bounds and he declared "when sixteen years ago, I uerged as a thing to be sought - that for which I joined Tycho Brahe ..... at last, I have brought to light and I recognize its truth beyond my findest expectations ..... The die is cast, the book is written, to be read either now or by posterity, I care not which, it may well wait a century for a reader, as God has waited six thousand years for an observer."

The "book" did not have to wait for a century and indeed constituted the starting point for the scientific revolution that we witnessed in the succeeding centuries. First and foremost, the Kepler laws constituted a triumph for the Copernican

system and thus provided a pioneering and desirable change in our perception and perspective from the self-centric world to the extra-centric one. This view, much against the ecclesiastical church doctrine, was to play a crucial role later in our quest for knowledge of the Universe around us. With this, the earth dissolved its identity and joined as a member of the solar system family, though a unique member indeed, all for the sake of harmony!

Contemporaneously with Kepler (b.1571 - d.1630), Galileo Galilei (1564-1642) was carrying out experiments in the terrestrial laboratory which were to lay the foundations for the laws of motion as we know them today. Galileo is credited with the "law of inertia" which is the cornerstone of the laws of motion. This law was deduced essentially from idealization based on day-to-day observations and also, I suppose, by carrying out explicit experiments.

Recall Brahma Gupta Aryabhatta debate

Did these terrestrial observations on motion have anything to do with the motions of planets in the heavens? In particular, would the laws of motion as deduced through experiments on terrestrial objects apply equally well to the motion of the heavenly objects? And, could Kepler's laws on planetary motion be related to and understood in terms of the laws of motion as deduced by studying terrestrial motions?

This was a very important question in the history of scientific evolution. For, it sought, for the first time, to

extend the territory of a law to other domains. From terrestrial to extra-terrestrial and vice-versa. The answer to it was provided in the affirmative by Isaac Newton (1642-1727) who was born the year Galileo died, and in a sense continued and completed the task which Galileo started. He also thereby met the challenge of understanding the laws that Kepler left behind. Cajoled and persuaded by Halley to apply his "laws of motion" which he had not published, to the motion of the Comet (which Halley had observed), the unwilling Me. Newton was able to explain all the previous recorded sightings of the comet and predict its next appearance.

It was for the first time that a prediction was made and subsequently verified. It was a triumph of the methods of science, of the methods of threotical physics. More importantly, however, it established the principle of the "universality of the laws of motion". This principle of the universality of the physical laws was later to be extended to the other laws of physics without hesitation.

With Isaac Newton was thus born not only the science of mechanics, but also the science of theoretical physics. While Galileo is regarded as the founder of "experimental science", Newton is truly the founder of theoretical physics.

This inter-relationship between the motions on earth and motions in the heavens through the universal laws governing them, thus constitutes the first example of a quest for harmony

between the earth and the Universe around us.

Electromagnetism - A Quest for Partners:

The next century witnessed the reformulation of the laws of mechanics at the hands of Lagrange, Hamilton and Gauss, no new advances were made in the discovery of physical laws. It was only with Cavendish and Coulomb in the later part of the 18th century that the presence of electrical changes and forces between them were discovered. This was followed by the discovery of electrical current by Volta and discovery of the magnetic effects of currents by Ampère.

But it was Michael Faraday (1791-1867) who made the most pioneering discovery of the time which showed that there existed a relationship, a partnership between electricity and magnetism: that a time rate of change of magnetic field leads to the generation of an electrical field of the induction type. This pointed towards a synthesis of the apparently different physical phenomena, namely electricity and magnetism. The process of the synthesis of the two disciplines was, as we know, completed by Maxwell by introduction of the displacement current.

The resulting laws of electromagnetism which incorporates the Coulomb law of inverse square force) in the Poisson eqn., the Faraday law of induction and the Ampère law supplemented by the displacement current are now referred to as the Maxwell's equations.

The last equation merely expresses the empirical fact that no magnetic monopoles have so far been found.

Needless to say, the electromagnetic theory as embodied by Maxwell's equations has unified not only electricity and magnetism, but the entire spectrum of entities, namely light, of various colours, heat, radiation and x-rays that we have been so familiar with.

Once again, the laws enunciated and new equations postulated about electromagnetism have brought about an unprecedented synthesis of a variety of diverse phenomena which were apparently hitherto unrelated to each other. It was again a landmark of a magnitude comparable to that of the discovery of mechanics as embodied in Newton's law of motion. Once again, we had mathematical equation, which not only synthesized, but which also gave us the power to make predictions about new phenomena related to electromagnetism.

If one were now to use the principle of the universality of these laws and extend their applicability to extra-terrestrial domains, then these equations would provide us means to study the electromagnetic phenomena in these extra-terrestrial domains and to understand various processes in terms of these laws.

The Atomic Quest - Journey into the Microcosm :.

While astronomers did continue to look at the heavens through their telescopes and making spectroscopic observations, there were no major advances in our frontiers of astronomy. The focus of attention through the 19th century was the thermodynamic behaviour and the constitution of matter.

The chemists of the 18th and 19th century were the ones who were responsible for making advances towards our understanding of the constitution of matter, through the work of John Dalton, Avogadro and others. By the end of the 19th century, the atomic theory of matter was firmly established and generally accepted though there were still some diehards who refused to do so.

What was an atom made of? This was now the question which occupied the minds of the physicists. Following the discovery of electron by J.J. Thomson, Kelvin proposed in 1902, an electrical model of the atom, where the positive charge was distributed uniformly and electrons were embedded in it like "raisins-in-bread". But it could not last.

The Rutherford Atom

Can a solar system like structure exist at the micro-scale, say in the context of the structure of the atom? I do not know whether Rutherford actually did ask such a question in his quest for the structure of the atom when he performed his experiment on the scattering of α-particle by solid targets, but the answer to the above question that he got from his experiments was in the affirmative.

Thus, for the first time a model of a system (solar system) - the Copernican model - in the macrocosm, found an image in the microcosm separated in dimensions by an order 10^{23} (taking the dimension of solar system 100 AU and atomic dimension 1 AU = 10^{-8} cm). An atom was found essentially to be a solar system in the microcosm.

This also led to the realization that there are two widely different interactions in nature: the gravitational interaction and the electromagnetic interactions. The relative strength is essentially given by $e^2/Gm^2 \approx 10^{43}$. (This power is almost double what separates the microcosm from the macrocosm at the solar system dimensions).

The two features pointed out above, namely (i) the application of concepts of microcosm to macrocosm and vice versa and secondly (ii) comparison of the strengths of interaction, occur again and again in the history of evolution of microcosm and macrocosm.

Lord Kelvin's two dark clouds

Towards the turn of the last century, Lord Kelvin seemed rather satisfied with the state of understanding of the physical world. Yet he was a little concerned and he referred to the existence of "two dark clouds" on the horizons of physics. These were

(i) The ultraviolet catastrophe of the Rayleigh-Jean law

and (ii) The negative result of the Michelson-Morley experiment.

As it turned out, these really were the "dark clouds". Because, out of them came two new horizons which constituted the corner-stones of the revolution in physics in the twentieth century.

The resolution of the ultraviolet catastrophe culminated in the birth of the "quantum" leading to the quantum revolution.

While the negative result of the Michelson-Morley experiment was revolsed in terms of the "special theory of relativity" enunciated by Einstein, an unknown clerk in the patent office in 1905. It must, however, be stated that the M-M experiment was not the motivation for Einstein's relativity. In fact, Einstein was not probably aware of the result of the M-M experiment.

The two new horizons that were so discovered, it ought to be noted, dominated the evolution of the Microcosm and the Macrocosm.

Between 1910 and 1915, Einstein developed what he termed as the "General Theory of Relativity" which was essentially

a theory of Gravitation. It was not motivated by any known experimental fact except the empirical law discovered by Galileo about three hundred years ago, namely the "principle of equivalence". The whole structure of the theory is then built over this single innocent looking principle [namely "all bodies fall under a gravitational field with the same acceleration independent of their masses". (This is indeed what Galileo found from the Tower of Pisa)] using pure reasoning.

In Weyl's words :

"It is the greatest example of the power of speculative thought"

and he continued elsewhere.

"It is as if a wall which separated us from truth has collapsed. Wider expanses and greater depths are new exposed to the searching eyes of knowledge, regime of which we had not even a presentiment. It has brought us much nearer to grasping the plan that underlies all physical happening".

And Eddington in his Space. Time and Gravity (1920) wrote:

"By his theory of relativity, Albert Einstein has provoked a revolution of thought in physical science".

And, finally Einstein himself said of his theory:

"Scarcely anyone who has fully understood this theory can escape from its magic; the theory represents a genuine triumph of the method of the absolute differential calculus of Christoffel, Kicci and Levi Civita".

The Einstein theory of gravitation (or general relativity) is described by the following equations :

$$R_{ik} - \frac{1}{2} g_{ik} R = -\frac{8\pi G}{C^4} T_{ik}$$

where

R_{ik} = Ricci Tensor, R = Ricci scalar

g_{ik} = space time metric, G = gravitational const.

and C = speed of light.

Einstein's theory, as a theory of gravitation theory of the Universe:

Einstein immediately realized that he could apply his theory to the Universe, the Macrocosm. He thus made three simplifying assumptions for the large scale structures in it :

(i) The Universe is homogeneous

(ii) The Universe is isotropic

(iii) The Universe is static

The Einstein equations thus provided for the first time a framework which enabled one to ask questions about the "Macrocosm" beyond the realm of pure speculation. They also enabled one to make assumptions (such as (i), (ii) & (iii) above) about the large scale structures in the Macrocosm and compare their consequences with observations.

One of Kelvin's dark cloud thus led us on to the path to the Macrocosm.

Coming to Einstein's assumptions (i) and (ii), quite clearly the Universe is neither homogeneous nor isotropic on small scale. They refer to the density on a sufficiently large scale.

Einstein soon found (1917), however, that no static solution of his original equations were possible which were both homogeneous and isotropic. He needed an extra term to add to his equations - the Cosmological term g_{ik} in order to obtain static solution. Einstein, of course, thought that the Universe was static or time stationary.

Friedman, however, dispensing with the assumption (iii) obtained in 1922 an expanding solution - an expanding Universe. This was also obtained independently by Lemaitre in 1927.

Unaware of the Friedman solution of the expanding Universe, Hubble made in 1929 a most epoch-making discovery when he measured the red-shifts of the distant galaxies. He found that the larger the distance of the galaxy was from the earth, the more was the red-shift of the light from the galaxy. This meant that all galaxies were receding from our galaxies in all directions. And since our galaxy is not supposed to be any preferred galaxy, all galaxies, it ought to be concluded, are receding from each other.

Fig. shows the original Hubble diagram of red-shift vs. distance from which he concluded the expansion of the Universe.

Back to the Microcosm

Perhaps, I have gotten ahead of myself in the Macrocosm, leaving behind the very important developments in the realm of the "microcosm" which had, in turn, great impact on our understanding and further exploration of the macrocosm.

Lord Kelvin's other 'dark cloud', namely the ultraviolet catastrophe of the Rayleigh-Jeans law gave birth to the quantum.

Very careful measurements by Lummer and Pringsheim and others of the Black-Body radiation spectrum had established the form of the latter. But it was not what the classical theory embodied in the Rayleigh-Jeans law gave. It agrees with the latter only in the long wave length limit.

Planck in trying to understand the form of the B-B spectrum in terms of the concepts of statistical mechanics, applied to radiation was "compelled" to introduce a concept of a "quantum of radiation" in terms of which energy was exchanged between matter and radiation. It was an "act of desperation" on the part of Planck, as he put in, (as there was no other alternative left) which he did mot reluctantly.

Thus the quantum was born in the context of radiation in the closing days of 1900 heralding a new quantum era in the 20th century.

Large amount of spectroscopic data had accumulated over the many years without any clue as to the origin of the emission

of light in discrete spectral lines as the spectroscopic observations showed. Many empirical relations pointing out the systematics had, in fact, been obtained. The situation was ripe for a theory to be put forward which could explain these observations.

Thus, soon after the formulation of the Rutherford atom - which could be regarded as the Copernican model of the atom - Bohr gave in 1911 a model of the atom which almost instantly explained the atomic spectra in an almost magical way.

The Bohr atomic model:
The first major triumph of the Quantum Theory;

From Atoms to Stars - the birth of Astrophysics

While the Rutherford-Bohr model of atom owes its concept to the solar system, it was the turn of the microcosm to help unravel the secret of the Macrocosm, an example of what may be regarded as a quest of the Macrocosm by the Microcosm.

In what should be regarded as a most pioneering theoretical advance of the time, Meghnad Saha in 1920, put forward an idea and a formula based on it that was to form the basis of all astrophysical investigations in later years. He should thus be regarded as the father of astrophysics - indeed the first astrophysicist.

It was the so-called

"Saha Ionization Formula"

Evolution of the Microcosm:

- Rutherford - Bohr atom ⇒ the first major triumph of quantum theory. (1911)
- Quantum statistics: Bose - Einsteins (1924), Fermi - Dirac
- Quantum Mechanics: Schrödinger (1926) and Heisenberg (1925).
- Dirac electron - positron. (1930)

FROM ATOMS TO STARS

Application of Microcosm concepts to Macrocosm (stars).

→ **Mystery of the stellar spectra:**

- Thermal Ionization ⇒ Meghanad Saha (1920)

→ Saha Ionization formula

Birth of Astrophysics

→ Involves the "structure of atoms" and elements of statistical mechanics - Boltzman factor $\exp(-e\Phi/kT)$

Experimental basis of the chemical constitution of stars.
— A most pioneering theoretical advance of the time.

Why are atoms as they are ?
Why are stars as they are ?

Next fascinating application →
White Dwarf, Neutron Stars.
by S. Chandrasekhar.

He asks: "Why are atoms as they are"?

A combination of natural constants, e, m & $\hbar$ determines the "atomic length"
– the Bohr radius

$$a_0 = \hbar^2/me^2 \simeq 0.5 \times 10^{-8} \text{ cm}.$$

Thus the atoms are as they are:
– because the combination $(\hbar^2/me^2)$ provides a correct measure for their dimensions

Or the theory of the atom is such that the dimension of the atom is expressible in terms of only the natural constants.

Can one ask the same question about stars?

Namely,

Can the mass of a star M_* be written expressible in terms only of some appropriate natural numbers?

G, m_H, $\hbar$ and c (in this case)

G → Gravitational constant; m_H → proton mass; $\hbar$ → Planck const.; c → Speed of light

A combination which has the dimension of Mass is

$$M_* = \left(\frac{\hbar c}{G}\right)^{3/2} \frac{1}{m_H^2} \approx 29\, M_\odot$$

Can the theory of stars be as simple that their mass can be expressed as some units in terms of M_*?

Surprising as it may seem, it turns out that it is indeed so

Application to "White Dwarfs":

$\rho_\odot \approx \rho_{water}$

After all the nuclear burning (exhausting all source of energy)

→ a star finally contracts, settles down to an equilibrium: pressure grad. = gravit force.

$$\frac{\partial p}{\partial r} \approx \frac{GM}{r^2}\rho \Rightarrow \text{White Dwarf}$$

$\rho_{WD} \approx 10^8$ gm cm^{-3} | Matter in the form of nuclei + some free electrons.

Using relativistic equation of state Chandrasekhar found that a for a W.D. to equilibrium is possible only for

$$M \lesssim 1.4\, M_\odot \quad \left(\equiv 0.05 \left(\frac{hc}{G}\right)^{3/2} \frac{1}{m_H^2}\right)$$

→ Chandrasekhar limit.

Important to remember & note: according to the theory

- M_{WD} is (again) a fraction of $M_* = (hc/G)^{3/2} \frac{1}{m_H^2}$.
- It is remarkable that "quantum theory" a characteristic of the "microcosm" and relativity determines the state of a macro-object such as the W-D.

[Showing how physics derived from the microcosm determines the Macrocosm

Stars with larger mass? What happens?:

- after they exhaust their source of energy.
- May eject a fraction of mass during contraction so that it comes below M_{ch}.
- May contract further without ejection increasing densities to nuclear matter densities $\sim 10^{12} - 10^{14}$ gm/cc.

→ Neutron stars [Landau 1932]

Internuclear force would balance gravitational force.

Because of "exclusion principle", neutron cannot decay $n \to p + e^- + \bar{\nu}$.

Or we could have

$e^- + p \to n + \nu$.

$\Longrightarrow$ Pulsars

For "neutron stars" $M \lesssim 2M_\odot$.

For $M \gtrsim 4\text{-}6\ M_\odot$, there may be high core densities and temperatures $\to$ explosive nucleosynthesis $\to$ ejection of mass.

$\to$ "Supernovae Explosion."

$M \gtrsim 10\ M_\odot$:

Contraction cannot be arrested by any force if mass ejection does not occur.

$\Longrightarrow$ Black Hole.

Lord Kelvin's Second "Dark Cloud":

(negative result of the Michelson-Morley experiment)

↓ Theory of Relativity: special + General.

→ Overthrow of absolute space-time of Newton.

Galileo's "principle of equivalence" $m_i \equiv m_g$

— Cornerstone of the theory.

→ "All bodies fall under gravitational field with the same acceleration independent of their masses."

Einstein (1910–1915) developed G.R. using POE as the only empirical fact.

H. Weyl

"It is the greatest example of the power of speculative thought."

Einsteins equations :

$$R_{ik} - \frac{1}{2} g_{ik} R = -\frac{8\pi G}{c^4} T_{ik}$$ → Energy Momentum Tensor.

R_{ik} ≡ Ricci Tensor, R ≡ Ricci scalar

g_{ik} ≡ space-time metric

G ≡ gravitational const, c ≡ speed of light

The theory provides - a theory of gravitation
- a theory of the Universe
- a framework for the description of the Macrocosm whose evolution would be determined by the energy-momentum tensor T_{ik} corresponding to the matter present.

But it does not say what kind of matter and radiation ought to be there.

It has to be supplied from our knowledge of the microcosm :

protons, electrons, neutrinos, photons .....

left) which he did most reluctantly

Thus the quantum was born in the context of radiation in the closing days of 1900 heralding a new quantum era in the 20th century.

Large amount of spectroscopic data had collected accumulated over the many years without any clue as to the origin of the emission of light in discrete spectral lines as the spectroscopic observations showed. Many empirical relations pointing out the

~~Within two years of~~ the systematics had in fact been obtained. The stratum was ripe for a theory to be put forward which could explain these observations.

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Einstein's solution: (1917)

Simplifying assumptions:

(i) Universe is homogeneous (on large scale)
(ii) " " isotropic (" " " ")
(iii) " " static (on long time scale)

No static solution of his field equations was found possible.

So he added Cosmological term λg_{ik}

Einstein's solution was static and predicted no red-shifts (known to be existing) of modified equations

de Sitter (1917) found another solution: appeared to be static, but predicted

(red shift) ~ (distance) !!

Spurred by the prediction of de Sitter's "expanding" solution Hubble made observations of the red shift of galaxies and found that Doppler shifts of galaxies varied linearly with distances

- the distance being determined by the Cepheid variables in a galaxy.

Red shifts - Hubble plates
- Hubble diagram.

The Cosmological Principle:

An observer in a typical galaxy should see all other galaxies moving with the same pattern of velocities whatever typical galaxy the observer happens to be riding in.

Friedman Model:

Recession of velocities found by Hubble in accordance with the "Cosmological Principle" was in agreement with

(1922) Friedman Model (of expanding Universe)

↓

general homogeneous isotropic solution of the original Einstein's equations.

Using the Saha formula one could then identify not only the elements present in stars, but their temperature of the stars as well.

As is well known, all the work relating to the ~~chemical~~ evolution of stars including the thermonuclear cooking of elements in the stars is based on the information derived using the Saha formula. The object here is not to show how it is done, but only to point again the importance of applying concepts ~~based on earth-based~~ derived from earth based laboratory to extra-terrestrial situations

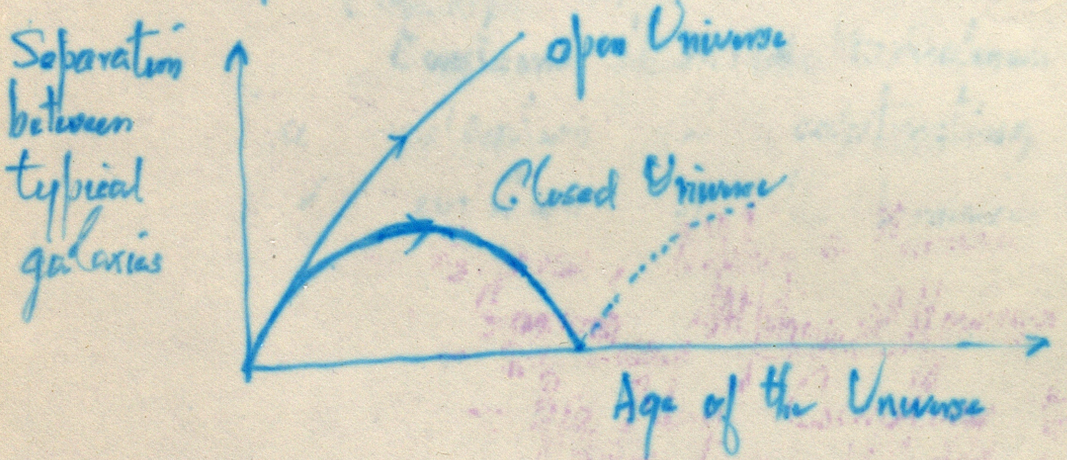
The next important such application was made in an even more spectacular ~~fashion by~~ case by another Indian (or India-born) astrophysicist Subrahmanyam Chandrasekhar: By applying methods of quantum (relativistic) statistical mechanics to not any small scale terrestrial object but to a star, namely a "white dwarf", as if it were a solid body in a terrestrial laboratory, he ~~was able to~~ derived a most spectacular result namely that there exists a critical mass M_c, $M_c \simeq 1.4\, M_\odot$, beyond which a white draw could not

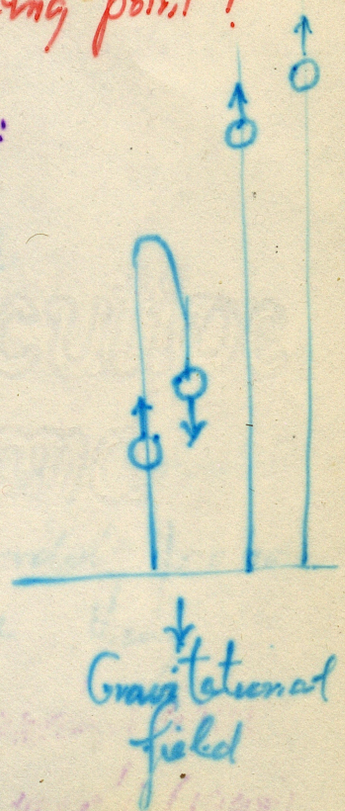
If the Universe is now expanding
Does it have a beginning ? A starting point ?

Friedman model gives two possibilities :

- Expanding + just expanding
- Oscillating Universe

Depending on the "initial density"





What would happen if we ran the Universe backwards ?

- Distances between the galaxies would decrease and they would collide
- Stars would collide and possibly fuse
- Interstellar gas would be compressed and the Universe would heat up
- There will be radiation all around at high T.

Thermal History of the Universe :

- Nuclei collide and may break up etc.

Evolution of the Universe :

Einstein's theory + Frudman model provided a motivation for constructing a theory of evolution of the Universe

- Gamow, Alpher + Herman 1940's (1948) — "Big Bang" Cosmology

$\frac{n_{photon}}{n_{nuclear}} \approx 10^9$ to account for present day nuclear abundance of light elements

↓ Residual (relic) background temperature $\approx 5^\circ K$ was predicted but not looked for !!

Controversy about "Big Bang" vs "Steady-state" Universe of Hoyle-Narlikar + Bondi

Herman Weyl:

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A.S. Eddington:

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"Scarcely anyone who has fully understood this theory can escape from its magic; the theory represents a genuine triumph of the method of the absolute differential calculus of Christoffel, Ricci and Levi Civita."

3°K - Radiation

Cosmic Microwave radiation Penzias & Wilson (1965)
(Measurement of Radio waves at high galactic Latitudes)

Greatest Cosmological discovery

settled the question in favour of the "Big Bang" !!

This is the radiation left over from the time when the Universe was effectively "opaque"

- photons were scattered strongly by the electrons "the Thomson fog".
- 10^8 times smaller & hotter
- $T \approx 3000$ °K

The PLASMA UNIVERSE

Ionization of H. & He would have occured just below this temperature !!

↓

essentially Saha ionization process.

On further compression to $T \sim 4000$ °K

Energy of radiation > Energy of matter

$(10^9 \text{ photons})(h\nu) > (\text{proton energy})$

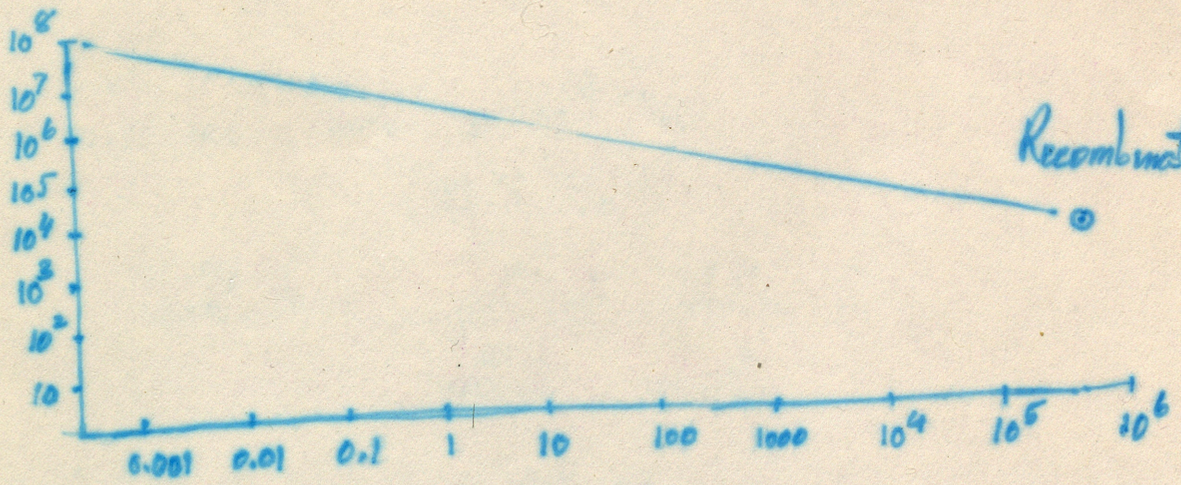
- $h\nu \gtrsim 10^{-9}$ proton energy (~ 1 GeV)

$h\nu \gtrsim 0.4$ eV

$T \gtrsim 4000$ °K

This correspond to the age $\approx 700{,}000$ Yrs.

Radiation dominated era:



From 700,000 yrs to 3 minutes

Contents of the Universe Temp at 3 min $\sim 10^9$ °K

electrons, protons, He^{++} + neutrinos

↓ 70-75% | 25-30%

Further Compression:

Helium nuclei break up at

→ t = 13 sec, $T \sim 3 \times 10^9$ °K

Contents: protons, neutrons, electrons

+ PHOTONS.

e^+e^- pair production starts from photons

→ t = 1 sec, $T \sim 10^{10}$ °K.

neutrinos start to couple with other part.

$t = 0.11$ sec Temp 3×10^{10} °K
(2.6 Mev)

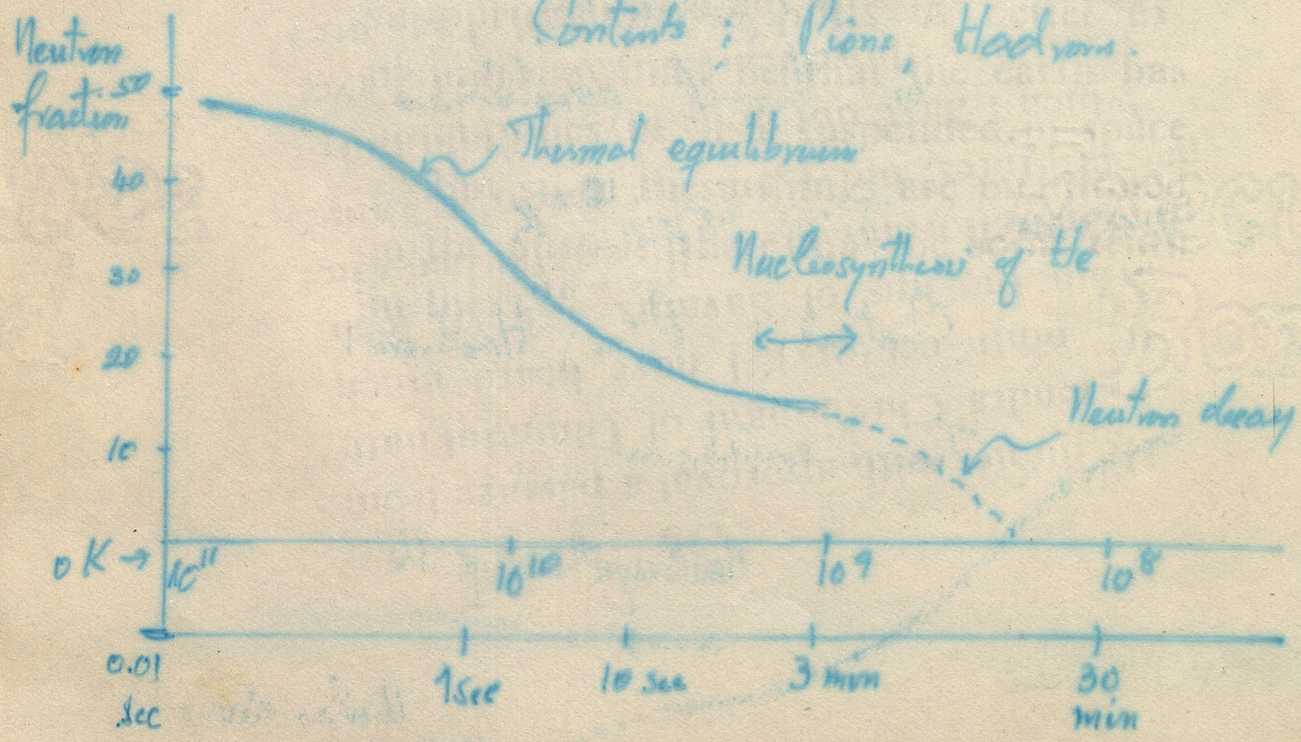
Contents : e^+ e^- photons
protons, neutrons

$t = 0.01$ sec. $T \sim 10^{11}$ °K
(5.6 Mev)

e^+, e^-, ν (neutrino)
γ (photons)
in thermal equilibrium

$t \leq 0.01$ sec $T > 1.5 \times 10^{12}$ °K

Contents : Pions, Hadrons.



He quotes with approval a passage from Rasendra Chintamani of Dhunduknath (C. ninth century) 'I have heard much from the lips of Savants. I have seen many (formulae) well established in Scriptures, but I am not recording any which I have not done myself. I am only recording those fearlessly which I have carried out with my own hand. They are alone to be regarded as real teachers who can show by experiments what they teach. They are the deserving pupils, who having learnt from their teachers can actually perform them, and improve upon them. The test are merely stage actors'[14]. He also notes among achievements of ancient Indian chemistry that Indians knew flame-test for elements in ores: 'Copper yields a blue flame ... that of tin is pigeon coloured ... that of lead is pale-tinted ... that of iron is tawny ... that of 'peacock ore is red' (*Rasarata Samuccaya*, C. 8th century)[15].

May be opened for postal inspection
Für postamtliche Prüfung hier öffnen
Peut être ouvert pour inspection postale

