High Energy Physics : a (historical) perspective

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For SERC School, December 2002

Prologue

- Ancients : Greek, Indian, ... Kalidasa
- Protohistory :
  - Astronomy – Ptolemy to Herschel
  - Experiment – Galelio, Coulomb, Oetovos
  - Phenomenology – valence, Periodic table, Balmer series
  - Theory – universal Gravitation, electromagnetism

Note the color scheme

- Cool blue Cosmos
- High energy experiments
- Rolling pastures of phenomenology
- Quirky orange of theory

Beginnings – 1890-1920

The atomic theory of matter

- The Cosmos – Lowell telescope
- Radioactivity – Bequerel, Poincare
  - Thomson's discovery of the electron
  - Rutherford
  - Bubble chamber (1912) C T R Wilson
- Planck's hypothesis, photoelectric effect
  - Bohr model
  - de Brogli's matter waves
  - Pauli's Exclusion Principle
- General Theory of Relativity, Schwarzschild solution

1920-30

- The expanding Universe (Wirtz and Lundmark, Hubble)
- van de Graaf generator (US), Cockcroft and Walton (Cambridge)
  Nuclear decays, the neutron (Chadwick)
- The neutrino (Pauli), the positron (Dirac), antiparticles in general
- Quantum Mechanics (Heisenberg, Schrodinger, Dirac)
  The Cosmological constant

1930-40

- Positron (1933) Anderson
  The μ-"meson" (1937) Anderson ...
  Hubble and Humason at 100 in. Mt. Wilson reflector
- the cyclotron (1934) Lawrence
- Yukawa theory of exchange force, (1935)
  - Fermi's four-fermion theory β decay
  - Isotopic spin invariance (Heisenberg)
  - The S-matrix (Heisenberg, Wheeler)
- "Second quantization" (a.k.a. the actual RQM),
  Anticommutators (Jordan and Wigner),
  Quantization of Klein-Gordon (Klein and Jordan)
  Old QED; divergence of Relativistic corrections
  Chandrasekhar, Oppenheimer on final states of degenerate stars
  Kaluza-Klein theory

The bomb ... 1940-50

- The π-meson (Lattes, ... Powell) in balloon flights
- Microwave technology, the Lamb shift
- Lamb's calculation and Kramer's proposal
  Calculations of "Alpher Bethe and Gamow" on formation of elements and prediction of remnant photon gas
- Path integral formulation of Quantum Mechanics
  E. C. G. Stueckelberg
  Lamb shift, $(g-2)$ a la Feynman and Schwinger
  Renormalisation : also, Dyson, Tomonaga, Oppenheimer, Weisskopf
  Schwinger's Green function approach; Kallen, Lehmann, ...

Contributions of Feynman and Schwinger

1950-60

- Mt Palomer 200 in reflector
  Galactic surveys – He abundance
- Bubble chamber
  Commissioning of Alternating Gradient Synchrotron machines at Brookhaven and CERN
  mesons and resonances
  Parity violation experiment
  strange particles, $\tau = \theta$ puzzle
- Conserved Vector Current and Partially Conserved Axial Vector Current
  The $V - A$ theory of Weak interactions (Sudarshan and Marshak, Feynman and Gell-Mann)
- Final touches to Renormalisation (Salam, Weinberg)
  The Intermediate Vector Boson hypothesis
  Local gauge invariance (Yang and Mills; Shaw)
  Fiber bundles (Ehresmann)

1960-70

- The CMBR. Pulsars. Quasars – Radio Astronomy
  Rotation curves of galaxies, missing matter or Dark Matter
- Linac at SLAC
  Discovery of CP violation 1964
  Proportionate multiwire chamber detectors – role of ultra-fast electronics (Charpak) and Stocastic Cooling to sustain intense beams (van der Meer) developed at CERN Scaling and parton hypothesis in D(eep) I(nelastic) S(cattering)
- The Eightfold Way (Gell-Mann and Ne'emann). Baryon number, Lepton number, Strangeness and Hypercharge.

1960-70 contd.

- Spontaneous Symmetry Breaking (Goldstone and Nambu)
  SSB in gauge theories (Higgs)
  The analytical S-matrix, the bootstrap hypothesis (Chew, Mandelstam ... (TIFR contribution))
  The quark hypothesis (Gell-Mann, Greenberg)
  The Weinberg-Salam model
  Anomaly – conflict of renormalisation with current conservation (Adler; Bell and Jackiw)
  The founding of ICTP Trieste

The grand victory parade ... 1970-80

- X-ray bursters, gamma ray bursters – satellite telescopy
  Solar neutrino deficiency (Davis)
- Detection of weak *neutral* current (CERN, 1973)
  τ lepton discovered (SLAC 1975)
  Discovery of J/ψ – charm quark (BNL, SLAC 1976)
  Lattice simulations begin
  Discovery of Υ – bottom quark (Fermilab 1977)
  3-jet and 4-jet events (PETRA - DESY)

Victory parade ... 1970-80 contd.

- Prediction of the fourth quark (Glashow-Iliopoulos-Maiani)
- Proof of renormalisability of SSB GFT (’t Hooft and Veltman)
  Deeper studies of SSB (Coleman; Coleman and E. Weinberg) and renormalisability : the “running coupling constant”
  Asymptotic freedom (Gross and Wilczek, Politzer) – scaling explained – the birth of QCD
  Lattice gauge theory (Wilson, Polyakov)
  Proposals for unification : (Pati-Salam, Georgi-Glashow)
  Coupling constant unification (Georgi, Quinn and Weinberg); proton decay
  S-matrix transmutes to String Theory (Virasoro, Scherk, Schwarz)
  Supersymmetry (Wess and Zumino, Volkov and Akulov)

Cosmos begins to open ... 1980-90

(The underground surfaces ...)

- "man in the sky" The inhomogeneous Universe
  commissioning of KEK, other proton decay experiments ...
  "but they don't decay" :-(
- $W^{\pm}$ and Z^0 (CERN 1983)
  27 km long LEP begins (CERN 1989)
  Lattice simulations in right earnest
- GUTs and cosmological consequences – monopoles, cosmic strings, detailed models of baryogenesis
  Supersymmetry signatures
- Inflationary Universe
  SuGra and reincarnation of Kaluza-Klein
  The first String Revolution (Green, Schwartz and Witten)
  Ashtekar's New Canonical Variables for QGra

The novel nineties ... 1990-2000

- COBE, IRAS observation of density perturbations
  Super Kamiokande and atmospheric neutrino anomaly – discovery of $\upsilon_e - \nu_\tau$ mixing and existence of neutrino mass
  H(ubble) S(pace) T(elescope) – SNa-I and Cosmological constant MAXIMA, BOOMRANG and DASI precision CMBR
- LEP and HERA – precision electroweak parameters
  Only three light neutrinos structure functions (HERA)
  The top quark at 176 GeV !! (FERMILAB 1995)
  Quark gluon plasma (CERN 2000)

Novel nineties contd.

- Precision phenomenolgy and B(eyond) S(tandard) M(odel)
  Failure of simplest $SU(5)$ unification
  Spurt to MSSM, $N = 1$ SuGra
- Eucledian QGra, BH radiation and Causality in QM
  The second String Revolution – unification of "distinct" String theories
  calculation of Black Hole entropy in String model
  AdS-CFT conjecture; holography

"What about Gravity?" – Abdus Salam 1996

- Feynman, Faddeev and Popov, Salam, 't Hooft and others – perturbative field theory of gravity – lack of renormalisability
- B. de Witt's trilogy in 1960's; monograph *"Dynamical Theory of Groups and Fields"* Covariant Green function approach.
- Constraint analysis and Wheeler-de Witt equation
- Schrodinger picture quantization *a la* Tomonaga (Gerlach).

- Path integral quantization Faddeev, Fradkin, Tyutin, Vilkovisky, Teitelboim (review/book by Teitelboim and Hennaux).
- Nonrenormalisation theorems in SUSY field theories. Would SuGra be renormalisable? 1-loop finiteness by symbolic computaion (van Nieuwenhuizen) and also by symmetry argument (Fradkin and Vilkovisky). 2-loop divergence by symbolic computation.
- Kaluza-Klein Super Gravity. Maximal $N = 8$ supergravity in 11 dimesions as unique theory (Salam, Witten). Ensures a gauge group E_8 in which unification groups of Particle Physics can be embedded.

- SuGra : Extremum necessarily local maximum? :-(
- Euclidean Quantum Gravity in path integral approach (Hawking) – the “no-boundary” proposal.
- Ashtekar’s New Canonical Variables. Constraint algebra polynomial and genralisation of GFT algebra. Loop variables.

- Strings as the panacea.
  - Linearised gravity automatically full gravity if coupling to conserved current demanded (Gupta, Deser).
  - QFT of massless spin-2 particles must be coupled only to conserved currents for S-matrix to exist (Weinberg).
  - Any massless spin-2 excitation must be Quantum Gravity theory.
  - Closed String theories possess a massless spin-2 excitations.

- Superstrings unified into M Theory live in 11 dimensions. Hopefully the field theory limit of this theory is the 11 dimensional SuGra. This SuGra would be automatically free of the renormalisation problems because ultraviolet behaviour would be governed by Superstring thoery which has not yet been found to possess divergences in loop calculations.

Wherein Kalidasa demonstrates his knowledge of modern theories ...

In the opening invokation नान्दि of the famous drama S'akuntalam,

या सृष्टिः स्रष्टुराद्या वहतिविधिहुतं
या हविर्या च होत्री ।
ये द्वे कालं विधत्तः श्रुतिविषयगुणा
या स्थिता व्याप्य विष्वम् ॥
यामाहुः सर्वबीजप्रकृतिरितियया
प्राणिनः प्राणवन्तः ।
प्रत्यक्षाभिः प्रपन्नस्तनुभिरवतुवस्
ताभिरष्टाभिरीशः ॥

श्रुतिविषयगुणा या स्थिता व्याप्य विष्वम् clearly shows knowledge of an all pervading medium for the propagation of sound.

More generally it could mean the universal medium for signals to propagate. *Æther* has been considered an obsolete concept throughout the Twentieth century, but circa year 2k, there is a revival of this under the name *quintessence*.

The phrase तनुभिर् ... ताभिरष्टाभिरीशः clearly refers to the Eightfold Way of manifestation of the Lord.