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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

ASTROPARTICLE PHYSICS (1988)

Abdus Salam

INTERNATIONAL ATOMIC ENERGY AGENCY

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International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization
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ASTROPARTICLE PHYSICS (1988)

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Abstract

A review of the present situation in particle physics, astrophysics and cosmology is attempted, which emphasises the unity of the subject.

1. Introduction

The twentieth century has been called the century of Science. There have been four standard models which have been developed during the second half of this century. These are:

1) The Plate Tectonics model in geology;

2) The Double Helix model in Biology;

3) The Hot Big Bang model in Astrophysics and Cosmology; and

4) The Standard $SU_c(3) \times SU_L(2) \times U(1)$ model in Particle Physics.

The major development during the last fifteen years has been the realisation that models 3) and 4) have converged. I shall speak mainly about this aspect of the subject in Part I of this talk.

In Part II, I shall concentrate on non-baryonic dark matter and searches for it. There are problems here of the greatest moment, common to both Cosmology and Particle Physics.

PART I

2. Historical Gifts

How models 3) and 4) have historically influenced each other may be seen in the following table:

Gifts of Particle Physics to Astrophysics and Cosmology		Gifts of Astrophysics and Cosmology to Particle Physics
Nucleosynthesis	$\Rightarrow$	Cosmic abundance of $H, D, H^3, He^3, He^4, Li^7$ $\Leftarrow$ # of ν < MeV in mass
Spontaneous symmetry breaking in: 1) the <u>Electroweak</u> unification	$\Rightarrow$	$\Leftarrow$ Temperature dependance of phase transitions $T_c \approx 250$ GeV, $t_{\text{cosmic}} \sim 10^{-12}$sec
2) the <u>Electronuclear</u> unification (grand unification, G.U.T.)	$\Rightarrow$	1) $\begin{cases} T_c \approx 10^{14}\text{GeV}, \ t_{\text{cosmic}} \sim 10^{-35}\text{sec} \\ \text{proton decay and } \overline{p} \text{ slaughter} \end{cases}$ 2) Cosmic strings predicted (by GUTS) as seeds of galaxies. 3) "Paleogeny vs. Neogeny" relevant for the problem of the "Large scale structure of the universe", i.e. did the large scale of the universe get determined by initial fluctuations when the universe was 10^{-35} secs old (i.e. in the epoch of electro–nuclear (GUT) breaking)?
Inflation Superstrings T.O.E. (Theory of Everything)	$\Rightarrow$	Cosmological relics (like monopoles) diluted by inflation
Non–accelerator experiments ν–oscillations (MSW–Bethe mechanism) to resolve the missing solar ν mystery		$\Leftarrow$ 1) Relics: Dark matter; Wimps (weakly interacting particles); Shadow matter and gravitational–wave detection. 2) γ–astronomy at very high energies e.g. $\approx 10^8$ GeV from CYGNUS-3X or similar extra–galactic sources. 3) ν–astronomy with SN87; clues to ν–masses, ν life–time, # of ν species as well as limits on Axion coupling

TABLE 1

I was at Cambridge when the theory of nucleo-synthesis was worked out by Fred Hoyle and others. At that time I thought that this was as it should be – Astrophysics should naturally receive inputs from Nuclear Particle Physics. When during the 1980s the converse started to happen with the numbers of ν species predicted by cosmologists (presumably) agreeing with the laboratory determination of this number, then the Particle Physicists sat up. Already during the 1970s, when it was realised that gauge symmetry restoration takes place at a critical temperature T_c, and one recalled that such high temperatures (of the order of 250 GeV for the electro–weak transition) had occurred in the early universe in the Hot Big Bang model, most Particle Physicists felt that they had to learn about the early universe and the phase transitions therein.

3. The Three Eras

I shall divide the history of the subject of Astroparticle Physics into Three Eras. Tables 2–6 and particularly the "Remarks" column in the tables will give a description of the Physics situation and the open problems.

1) The SPECULATIVE ERA including the Super–String epoch, the epoch of Inflation, G.U.T., Supersymmetry–breaking, up to the cosmic time when electroweak transition took place	$10^{-43} sec < t_{cosmic} < 10^{-12} sec$ Both Physics and Cosmology unknown
2) The ELECTROWEAK ERA up to the end of the Big Bang when matter came to dominate over radiation	$10^{-12} < t_{cosmic} < 10^{12} sec$ Both Physics and Astrophysics known and in accord with the standard models (3) and (4)
3) The LARGE SCALE MATTER ERA	$10^{12} sec < t_{cosmic} \leq 10^{18} sec$ Physics known but Astrophysics unknown

TABLE 2

4. The Speculative Era

EPOCHS	TEMPERATURE	MODALITY	REMARKS	
A) Quantum Birth of the Universe as a Quantum Fluctuation M^2 (universe) = 0 B) Two–dimensional (d=2) superstrings, string size $\leq 10^{-33}$ cms	$\geq 10^{19}$GeV (Planck mass)	Number of Bose matter fields = 26 (alternatively 10 Bose fields + Fermi fields are needed to cancel the conformal anomalies)	Riemann surfaces traced by closed strings (first rate mathematics of Riemann surfaces needed for Physics Research)	Important ingredient → Fermi–Bose Equivalence → $\Psi = e^{i\phi}$ in $d = 2$
C) Birth of space–time ("outer space") Epoch of one Force	$\geq 10^{19}$ GeV	d–dimensional space–time arises as zero modes of d spin–zero Bose fields	The theory describes $N = 1$ supergravity with nearly unique super–symmetric (SS) "inner space" $E_8 \times E_8'$ (or $SO(32)/Z_2$) for $d = 10$. The Yang–Mills fields corresponding to these groups arise miraculously as composite solitonic objects when $d = 36$ goes down to $d = 10$	Triumphs 1) One unified force (T.O.E.) String theory most likely to be finite (not just renormalizable) 2) The zero mass graviton emerges from the theory as does Einstein's gravitational Lagrangian
D) Descent to four space–time (d=4)	10^{19} GeV	Kaluza-Klein-like (e.g. orbifold or Calabi–Yau) compactification takes one down from $d = 10$ to $d = 4$ (or construct the so–called heterotic theories directly in four dimensions). Gauge symmetry broken by Higgs in the adjoint representation associated with Hosotani–Wilson loops	Tragedy ⇒	1) One loses the uniqueness of the theory, when $d = 10$ descends down to $d = 4$ (there can be more than several million theories in four dimensions)
		Massive pyrgons appear, where m^2 (pyrgon) = $N(e^2 M^2_{\text{planck}})$ where $N = 1, 2, 3, \ldots$ generically	Suggested experimental tests for this string theory (T.O.E.) are rather meagre, some of these are: A) extra one or two $Z^{0'}$ B) fractionally charged dyons, (even of zero small mass)	2) No descent yet gives the standard particle model $SU_c(3) \times SU_L(2) \times U(1)$ uniquely though the spectrum is basically correctly given, as is the # of generations. (This last # is a topological invariant in this theory.)
λ = the cosmological constant; the most outstanding unsolved problem in Astro–Particle Physics: explain in a natural manner why $\lambda_0 \approx 0$		For low–energy physics, such pyrgons are irrelevant (where only zero compared to Planck mass particles will be kept		$\lambda \approx M^4_{\text{planck}}$ (in general) radiatively: $\lambda = 0$ for exact (supersymmetry) $\lambda \propto M^4_{ss}$ if SS is broken at M_{ss}. At present $\lambda_0 = 10^{-122} M^4_{\text{planck}}$ empirically

TABLE 3

5. Speculative Era (continued)

THE INFLATIONARY EPOCH

EPOCHS	TEMPERATURE	MODALITY	REMARKS	OPEN PROBLEMS
E) Inflationary epoch (See Note 1). Use scalar field to motivate inflation (see Note 2)	10^{19}GeV?	Inflation solves problems of 1) Horizon 2) Flatness 3) Rotation 4) Fluctuations 5) Overabundance of Monopoles and Relic particles	Two forces now; Electro–nuclear (G.U.T.) + (gravity);	1) End of inflation? When? 2) The nature of phase transition which decouples gravity?
F) local electro–nuclear G.U.T. breaking $T_c \approx M_{GUT}$	10^{14}GeV	1) Proton–decay and $\overline{p}$ slaughter, through X–decays, which lead to baryogenesis where { X ⇒ Higgs or gauge particles in SU(5) GUT $qq \xrightarrow{X} \bar{q}\bar{\ell}$ i.e. proton ⇒ qqq → $\bar{\ell}$ } (other decay channels for other GUTS) 2) However, no experimental evidence for $p \to \pi^0 e^+$ decay up to $\tau_p \approx 10^{32}$ years. If $\tau_p \approx 10^{35}$ years, experiments will need to be done on the moon.	Topological defects when GUT breaks;	
Is there an epoch of electronuclear (GUT) unification at all?	An ideal GUT theory would have a gauge group which is not semi–simple (i.e. does not contain U(1) factors) in order to ensure quantization of all gauge charges.	3) Could baryogenesis happen much later in time when temperature is of the order of the electroweak?	1. Monopoles (π_2) ⇒ 2. Cosmic strings (π_1) ⇒ 3. Domain Walls (π_0) ⇒	Theory without inflation gives them as too abundant for comfort; mass of GUT monopole $\approx \frac{M_{GUT}}{\alpha}$ Good for galaxy seeding nuisance and unwanted at present

TABLE 4

TABLE 4 (continued)

EPOCHS	TEMPERATURE	MODALITY	REMARKS	OPEN PROBLEMS
Examples of possible GUT breaking: $E_6 \Rightarrow SO(10) \Rightarrow SU(5) \times U(1) \Rightarrow SU(3) \times SU(2) \times U(1)$ Other partial GUT schemes like $SU(4) \times SU_L(2) \times SU_R(2)$ are possible	Pati and Salam suggested that quark and lepton matter should not be treated separately and suggested placing $\binom{q}{\ell}$ into one multiplet of four colours $SU_c(4)$, the fourth colour being $B - L$. This construction was generalized by Georgi and Glashow who suggested putting $\binom{q}{\ell}$ and $\binom{q}{\bar{\ell}}$ into one multiplet of $SU(5)$. Georgi and Fritzsch and Minkowski later generalized $SU(5)$ to $SO(10)$.	ν_R predicted in SO(10) GUT If ν_R mass is m_R one obtains, $m_{\nu_L} = \frac{m^2(\text{charged lepton})}{m_R}$ from a see–saw mechanism	4. Note that if density of monopoles is $\approx$ Parker limit, the GUT monopoles of mass $10^{16} GeV$ would close the universe by themselves (Barish)	Experiment with MACRO in Gran Sasso will give 4 monopole events/yr. at Parker limit
G) Possible that *no* GUT epoch exists	*If no GUT epoch then only* 2 mass scales 10^3 GeV and 10^{19} GeV (supersymmetry breaking occurs at 10^3 GeV)?		*There are string inspired* theories, where there exists no T_c corresponding to GUT breaking (E_6 or SO(10)) but $E_8 \times E_8'$. E_8' is then broken dynamically by gravitino condensates and this in turn breaks supersymmetry $SU_c(3) \times SU_L(2) \times (U(1))^5 \times E_6'$ directly	

TABLE 4 (continued)

EPOCHS	TEMPERATURE	MODALITY	REMARKS	OPEN PROBLEMS
H) Goldstone Particles arise when a global symmetry is broken spontaneously.	⇒ Examples: 1) Axions may accompany Peccei–Quinn global symmetry breaking. (This symmetry was introduced to solve the problem of CP violation in QCD (The Peccei–Quinn global symmetry breaking due to chiral anomaly leads to a potential whose imaginary part is tiny and may give rise to a weak "fifth" force $\sim 10^{-5}$ times weaker than gravity, with a long range.) 2) Majorans and 3)Familons may be the same particle in a properly ordered GUT theory. (Majorans would bring about spontaneous breaking of lepton # and lead to double β–decay; familons could be responsible for global breaking of the family symmetry).	New mass-scale for axions, majorans and familons $\approx 10^{11}$ GeV with masses of the particles themselves being very small $\approx 10^{-5}$ electron modes Goldstone particles must have derivative coupling $\sim \frac{\partial}{m_{global}}$ with m_{global} large, perhaps $\simeq 10^{11}$ GeV	Goldstone particles must have zero mass due to spontaneous global symmetry breaking. They acquire small mass-pseudo–Goldstone particles- instantonically if global chiral anomaly is present.	
I) Supersymmetry breaking mass M_{ss}. $\approx 10^{3} - 10^{11}$ GeV			SS breaks at all Temperatures, $T > 0$, no T_c for this symmetry.	Local SS = supergravity → super Higgs effect i.e. spin 3/2 gravitino acquires a mass $\approx m_{SS}^{2} m_{\text{planck}}^{-1}$ (m_{SS} is spontantous SS breaking mass)

6. The Electroweak Era

The Second Era extends from just before electroweak transition sets in (which happens at 10^{-12} secs), up to just after "Big Bang" ends and matter dominates (10^{12}secs) over radiation.

4 EPOCHS			
	TEMPERATURE	t_{cosmic} (assuming standard model of cosmology)	REMARKS
Possible continuation of broken G.U.T. and broken supersymmetry epochs should truly belong to the "speculative" era	1. $10^5 - 10^8$ GeV	10^{-24} to 10^{-18} secs	New accelerator ideas (like Plasma beatwave) needed; new technology must be developed if accelerator Particle Physics is to survive beyond the year 2015 (say) otherwise costs will be too high and the accelerators unmanageably large.
	2. $10^2 - 10^5$ GeV	$10^{-18} - 10^{-12}$ secs (see Note 4).A minimal $SU(3) \times SU(2) \times U(1)$ supersymmetric standard model needs two Higgs doublets i.e. three live neutral Higgs + $H^{\pm}$ (in addition to photinos, gluinos, winos, zinos, higgsinos, squarks and sleptons). (Mass of one of the neutral Higgs $m_H < m_Z$ a fine prediction.)	Present technology for pp (and possibly for e^+e^- linear colliders) will carry through. Discoveries beyond the Standard Model of Particle Physics expected below 10^3 GeV, c.o.m. energies. Particularly of Supersymmetric partners of known particles produced in pairs (due to conservation of R quantum #. In general $R = -1$, for the new particles)
Standard Epoch; Broken electroweak theory (see Note 3) (up to quark–lepton transition around 1/10 GeV).	3. $1/10 - 10^2$ GeV	$10^{-12} - 10^{-4}$sec	Standard model of particle physics $SU_c(3) \times SU_L(2) \times U(1)$ ($T_c \approx G_F^{-1/2} \approx 250$ Gev) Electroweak symmetry breaking yields 1. W and Z masses $\approx$ 80 and 90 GeV; this and spin (one) of W and Z verified directly. 2. $SU_c(3)$ quark-hadronic transition (CERN) verified if J/ψ suppression takes place for high energy ionic collisions 3. Three families of quarks and leptons (except Top Quark all discovered) 4. Higgs not found yet

TABLE 5

4 EPOCHS			
	TEMPERATURE	t_{cosmic} assuming the standard model of cosmology)	Remarks
Family mystery 20 parameters (see Note 5) ↔ a mystery; Hope that GUT and eventually the string theory (T.O.E.) will determine these in terms of m_{planck} alone.		$sin^2\theta$–(the mixing between γ and Z^0) cannot be determined from standard model theory	In string theory, family mysteries are solved (by Witten) by associating it with the Euler # of the manifold (or orbifold) which arises when dimensionality of space time descends to $d = 4$
1/10 GeV → $\frac{1}{3}$ ev	4. $10^{-4} - 10^{12}$sec		Nucleosynthesis "Big Bang ends" with emission of Penzias–Wilson background radiation; matter begins to dominate over radiation

TABLE 5 (continued)

7. The Third Era

THE LARGE SCALE STRUCTURE OF THE UNIVERSE

	COSMIC TIME	TEMPERATURE	REMARKS
Physics and Astrophysics known	$\approx 10^{-4}s$	$\sim 10^2$MeV	$\pi\&\mu$ annihilation colour confinement
	$\approx 1s$	1 MeV	Neutrino decoupling
	$\approx 4s$	0.5 MeV	e^+ (slaughter)
	$\approx$ 3 min	0.1 MeV	D bottleneck, He synthesis
	$\approx 3 \times 10^4$ years	2 eV	non–relativistic matter domination
	$\approx 4 \times 10^5$years	0.3 eV	Atomic H formation "recombination"
Galaxies, Clusters, Super–clusters, form between 10^6 years and 10^{10} years. Physics known but astrophysics cloudy	$\approx$ 15 G years	10^{-3} eV $\approx$ (3^0K)	Present

TABLE 6

8. The Third Era (continued)

THE LARGE SCALE STRUCTURE IN THE UNIVERSE

1980s REVOLUTION

1. It was previously believed that galaxies, clusters and superclusters of galaxies are uniformly distributed in space.

However, the new picture evolving during the 1980s is that the 3– dimensional plots of redshifts are finding clusters of galaxies distributed on the surface of large "empty" bubbles. These have diameters 20 to 50 Mpcs, one to two orders of magnitude larger than the thickness of the surface of the bubbles.

2. It seems that billions of massive stars exploded becoming super novae, the blast waves from these explosions formed the empty bubbles. Galactic clusters formed where bubbles intersected.

3. One must be cautious however.

"Since many of the known highest-redshift objects were found by accident, and in any case their properties have not been uniquely predicted by any physical model, one must recognize that there is difficulty in making credible generalizations from these biased samples about events in the distant universe."

R. Kron

NOTES TO PART I

NOTE 1

TESTS OF INFLATION

1) $\Omega = 1 + 10^{-BIG\#}$.

2) Adiabatic density perturabations with the Harrison- Zeldovich spectrum.

3) Expected spectrum of gravitational waves with $\lambda \sim 1$ km up to 10^{28}cm. No spectrum of relic gravitational waves $< 1K$.

"In inflationary scenarios, primeval gravitons like any other pre–inflationary relic are exponentially diluted during inflation".

Starobinsky, Turner

4) The above remark about (zero–mass) gravitons may have relevance for any surviving zero–mass shadow matter which may be part of the second E_8' in the heterotic $E_8 \times E_8'$ string theories. Such shadow matter is supposed to interact with normal matter only through its shared gravitational interaction.

NOTE 2

INFLATIONARY CHAOTIC COSMOLOGY

According to A.D. Linde (Physics Today, September 1987 issue):

"The orthodox version of inflation assumed it to be a modest variation on the standard hot Big Bang theory. It was still assumed that there was an initial singularity at $t = 0$, that after the Planck time (about 10^{-43} seconds) the universe became hot, and that inflation was just a brief interlude in the evolution of the Universe".

This has changed. For example, in Linde's theory of chaotic inflation, consider a field φ which satisfies the Einstein-Friedman equations:

$$\ddot{\varphi} + 3H\dot{\varphi} = -m^2\varphi \tag{1}$$

$$H^2 + \frac{k}{R^2} = \frac{4\pi}{3M_p}(\dot{\varphi}^2 + m^2\varphi^2) \tag{2}$$

(Here $H = \frac{\dot{R}}{R}$.)

(1) It can be shown that if the initial value of the field $\varphi = \varphi_0 > 1/5\, M_p$, where $M_p = M_{Planck}$, the friction term in Eq.(1) makes the variation of the field φ very slow, so that one can neglect $\ddot{\varphi}$ in Eq.(1) and $\dot{\varphi}$ in (2). Making these approximations, one can solve

$$\varphi(t) = \varphi_0 - \frac{mM_p}{2\sqrt{3\pi}}t$$

$$R(t) = R_0\ exp\Big(\frac{2\pi}{M_p^2}[\varphi_0^2 - \varphi^2(t)]\Big)$$

where

$$R(t) = R_0\ exp(Ht)$$

and the Hubble "constant" H is given by

$$H(\varphi) \approx \sqrt{\frac{4\pi}{3}}\frac{m\varphi}{M_p}$$

(2) If the field φ is smaller than $1/5\, M_p$, the friction term in Eq.(1) becomes small, and φ oscillates rapidly near its equilibrium value of zero.

(3) For m of the order of $10^{-4}M_p$ this implies that in our simplest model the inflationary domains of the universe typically expand to 10^{10^8} times their original size!

(4) After expansion by a factor 10^{10^8} all initial inhomogeneities, monopoles and domain boundaries have been swept beyond the horizon.

The average amplitude of such perturbation generated during a time interval H^{-1} (in which the universe expands by a factor of e) is given by:

$$\frac{\delta\varphi}{\varphi} \approx \frac{H}{2\pi\varphi} = \frac{m}{3\pi M_p}$$

Perturbations of the field lead to perturbations of density that are just right for subsequent galaxy formation if m, the mass of the quantum of φ, is around $10^{-4}M_p$. (But why has φ the desirable mass? Is there a "natural" explanation?)

NOTE 3

NOTE ON THE STANDARD MODEL OF PARTICLE PHYSICS AND THE ROLE OF FERMI TRANSITION TEMPERATURE $T_c \approx 250\ GeV$

The standard model of today's particle physics describes three replicated families of quarks and leptons. The first family consists of the so-called up and down quarks (u_L, d_L) and (u_R, d_R) (L and R stand for left and right chirality of spin-1/2 particles). Each quark comes in three colours: red, yellow and blue. There are, in addition, three colourless leptons, (e_L, v_L) and e_R. Thus this family has 12 quarks and 3 leptons (altogether 15 two-component objects) with $30 \approx 2 \times 15$ degrees of freedom.

The second family has charm and strange quarks (c, s) (replacing the up and down (u, d) quarks) while the electron and its neutrino are replaced by the muon and its neutrino. Like the first family, there are 15 two-component objects. The third family likewise consists of top and bottom (t, b) quarks plus the tauon and its neutrino.

In addition to these $45 (= 3 \times 15)$ spin-(1/2) two-component objects, there are the 12 Yang-Mills-Shaw gauge spin-1 messengers corresponding to the symmetry $SU_c(3) \times SU_L(2) \times U(1)$ – the photon $\gamma, W^{\pm}, Z^0$ and eight (confined) gluons. Nine of these (γ and eight gluons) are massless. In addition, there should at least be one physical spin- zero Higgs H_0 giving a total minimum degrees of freedom $(118 = 3 \times 15 \times 2 + 9 \times 2 + 3 \times 3 + 1)$ for the particles in the standard model. All particles except the top quark and the Higgs in this list have been discovered and their masses and spins determined (even though the colour-carrying quarks and gluons are confined). (In this context, it is worth remarking that CERN data from $Sp\bar{p}S$ have confirmed the *theoretical (tree diagram) expectation* of $W_{\pm}, Z^0$ masses to within 1%. (Experiments give $81.8 \pm 1.5\ Gev$ for $W^{\pm}$ and $92.6 \pm 1.7\ GeV$ for Z^0 masses.) The model is unified: the γ and Z^0 mix, but the magnitude of the mixing is expressed as a parameter $(sin^2\theta)$ which remains to be fixed by experiment. The unification happens when the temperature is higher than the Fermi mass scale $G_F^{-1/2} \approx 250\ GeV$ which, according to the standard cosmological model occurred when the Universe was 10^{-12} sec. old. Before this phase transition occurred, there were three fundamental forces (electroweak, strong and gravitational). Afterwards, the electroweak force separated into electromagnetism and the weak nuclear force, with $W^{\pm}$ and Z^0 becoming massive.

NOTE 4

SUPERSYMMETRY (MATTER–FORCE–SYMMETRY)

Astounding Symmetry Discovered Theoretically around 1974

Astounding because: it connotes symmetry between fermions and bosons: i.e. symmetry between fermionic matter of $\frac{1}{2}$ or $\frac{3}{2}$, (objects which are *individualists* obeying the Pauli Exclusion Principle) and bosonic force messengers of spins–0 or 1 or 2 which are *collectivists* and like to congregate.

MINIMAL (BROKEN) SUPERSYMMETRY MODEL has two Higgs multiplets plus higgsinos.

No evidence has been found yet for the existence of partners of quarks or leptons up to $\approx 50\ GeV$. The most crucial open problem in particle physics is to discover if these particles exist (expectedly below 1000 GeV centre of mass energy). As remarked before, there are 2 Higgs doublets in this theory i.e. 3 live Higgs particles H_1, H_2, H_3 and $H^{\pm}$ with $m_{H_2} < m_z$.

NOTE 5

ACCELERATORS NOW AND IN THE FORESEEABLE FUTURE

YEAR	ACCELERATORS	$\sqrt{s}(GeV)$ centre of mass energy	CONSTITUENT ENERGY (peak –Max, GeV)$\sqrt{s}$	LUMINOSITY $(cm^{-2}sec^{-1})$	LOCALITY
1987	$Sp\bar{p}S$	900	$100-300\ qq, q\bar{q}$	10^{30}	CERN
1987	Tevatron	2,000	$200-600\ qq, q\bar{q}$	10^{30}	FERMILAB
1987	TRISTAN	$60(e^+e^-)$	60	8×10^{31}	Japan
1987	SLC	$100(e^+e^-)$	100	6×10^{30}	Stanford
1987	Bepc	$4(e^+e^-)$	4	5×10^{30}	Beijing
1989	LEP I	$100(e^+e^-)$	100	1.6×10^{31}	CERN
1995	LEP II	$200(e^+e^-)$	200	5×10^{31}	CERN
1991	UNK	3,000	300-900 $qq, q\bar{q}$	10^{31}	Serpukhov
1991	HERA (ep)	320	100-170	5×10^{31}	Hamburg
?	LHC(pp)	20,000	2,000-3,000	10^{33}	CERN
?	SSC(pp)	40,000	4,000-5,000	10^{33}	USA
?	CLIC(e^+e^-)	4,000	4,000	$10^{33}-10^{34}$	CERN
?	VLLP(e^+e^-)	4,000	4,000	$10^{33}-10^{34}$	Serpukhov
?	ELOISATRON (pp)	100,000	10,000-12,000	$10^{33}-10^{34}$	Sicily

The SSC is meeting opposition in the US because alleged of high costs - $5 billion over 5 years of construction. Compare this with the sums of monies already spent on a project like SDI which have amounted to $12.7 billion so far.

NOTE 5 (continued)

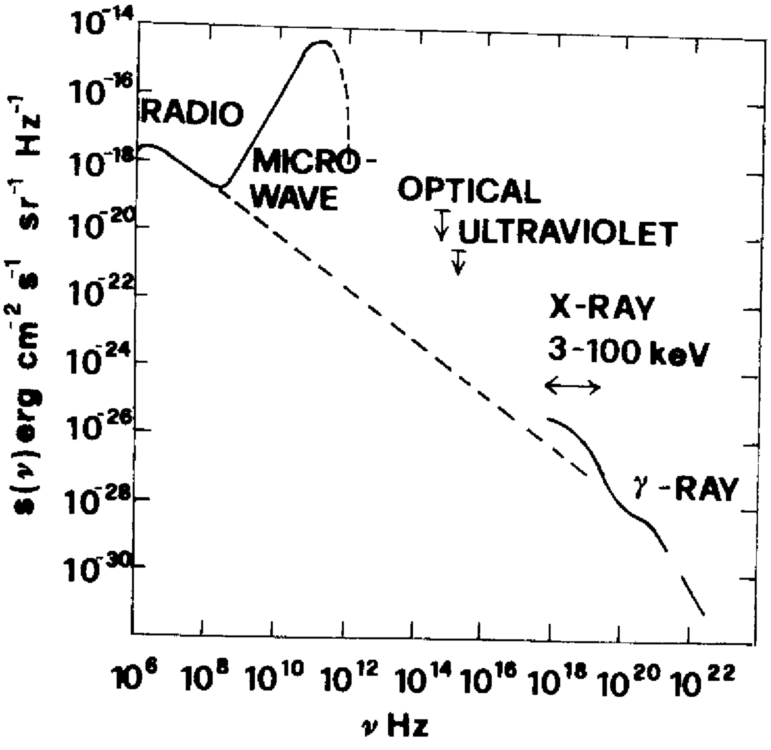
1) For the circular accelerators, the bending magnet may be improved by Superconductivity Technology, but the real limitation is due to synchrotron radiation $\propto (E^4)$. The cost and size of the accelerator increase as E^2. Here E is the c.m. energy.

2) For linear accelerators, the highest *Electric Field* gradients $\mathcal{E}$ achievable with today's technology, are at most around 1/10 GV per meter. Twenty years hence (when, for example, we may have mastered the technology of laser beat–wave plasma accelerators) the gradient may go up by a factor of 1000 – i.e. 1/10 TV per metre. This may mean that a 30 km long accelerator would produce center of mass energy $(\sqrt{s}) \simeq 10^4\ TeV$.

3) Chen and Noble have shown that if one can use longitudinal electron plasma waves in a metal, the electron density is of the order of $10^{22} cm^3$ (versus normal plasma densities of the order of $10^{14} - 10^{18} cm^3$) and we gain a factor of $\sqrt{n} \simeq 10^2 - 10^3$ (with the maximum energy limited to $10^5\ TeV$, on account of channeling radiation).

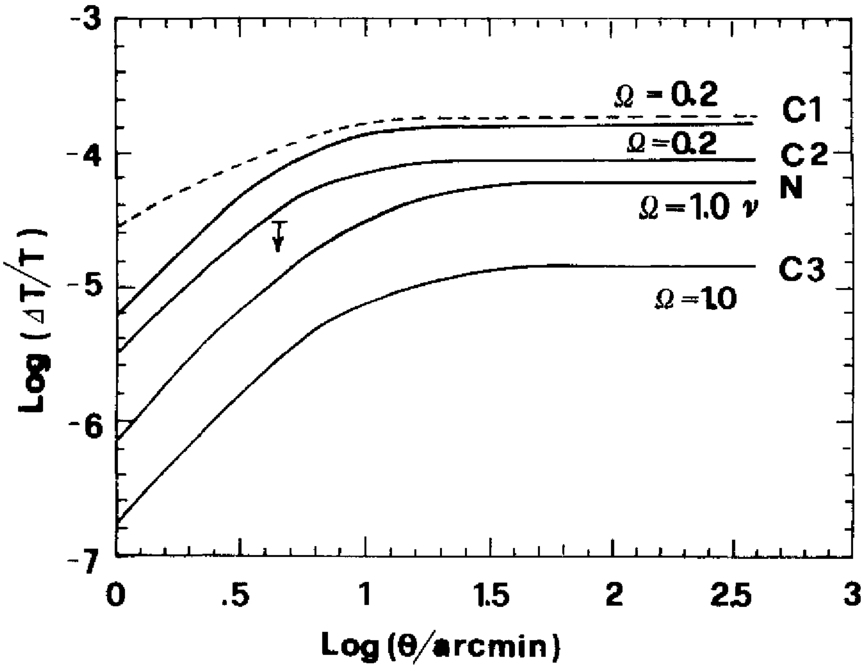
To be crazy, an accelerator around the moon may generate $10^6\ TeV$; an accelerator around the earth – as Fermi once conceived – may be capable of $\sqrt{s} \simeq 10^7\ TeV$, while an accelerator extending from earth to the sun would be capable of $\sqrt{s} \simeq 10^{11}\ TeV$ (with $\mathcal{E} \sim$ 1/10 TV/metre). In the same crazy strain, for an accelerator to be capable of generating $\sqrt{s} \simeq 10^{16}\ TeV$ (the theoretically favoured, Planck Energy) one would need an accelerator 10 light years long.

NOTE 6



The isotropic sky flux

NOTE 7



An example of the predictions of $\Delta T/T$ for different assumptions about the nature of the matter content of the universe, particularly the "dark matter" ("C" is for cold particles; "N" is for massive neutrinos.) Note that the single data point shown excludes some models and that measurements at comparable sensitivity, but $\theta \sim 30'$, would exclude most. Also, $H_0 = 75$ km/sec per Mpc, except for $Cl(H_0 = 50)$. (From Bond and Efstathiou, 1984).

PART II

"If all the matter of the universe were evenly scattered ..., and every particle had an innate gravity toward all the rest, ... matter could never convene into one mass ... but it would make an infinite number of great masses, scattered at great distances from one another ... and thus might sun and fixed stars be formed ..."

Newton

9. Dark Matter

The existence of dark matter was speculated upon 50 years ago by F. Zwicky. He showed that the visible mass of the galaxies in the coma cluster was inadequate to keep the cluster bound. Oort showed that the mass necessary to keep our own galaxy together was at least three times that concentrated into the observable stars. In recent years this has emerged as the major open problem of Cosmology and Particle Physics.

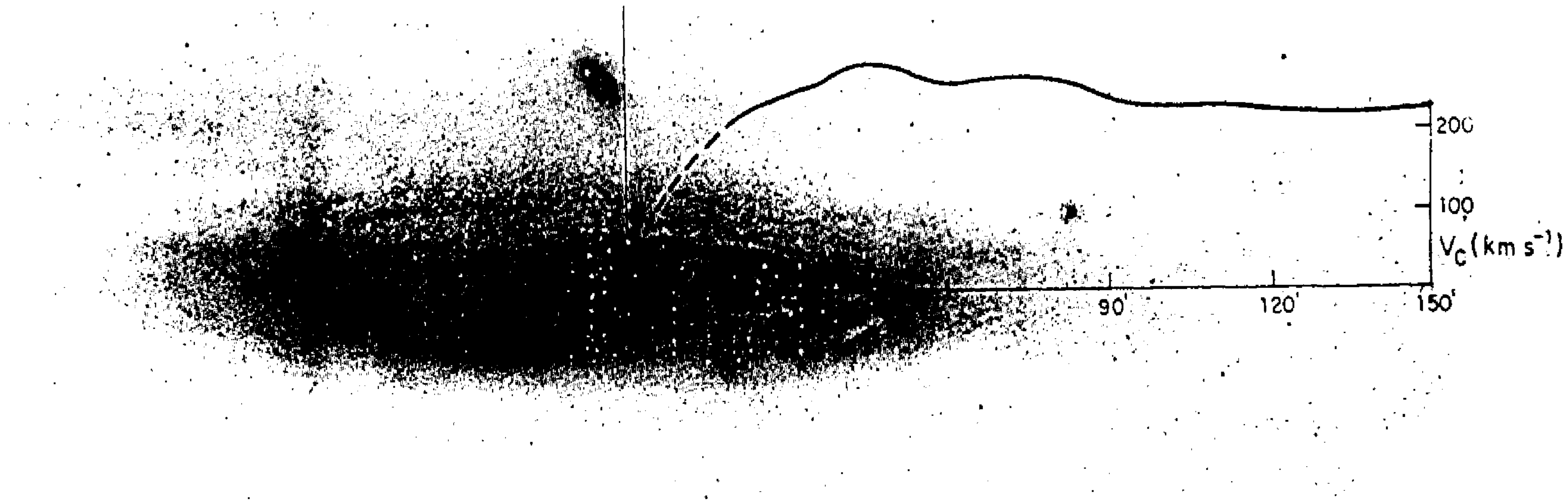


Fig. 1 — The Andromeda Galaxy M31 is shown with, superimposed on it, the rotation velocity of neutral hydrogen, inferred from 21 cm line radio studies. The rotation curve remains 'flat' even beyond the optical outer limits of the galaxy, implying that the outlying gas is 'feeling' the gravitational field of dark matter around the galaxy. (Courtesy of Morton Roberts.)

Define $\Omega = \rho/\rho_{\text{critical}}$ where $\rho_{\text{critical}}\ (= \rho_c) = \frac{3H^2}{8\pi G}$

Empirically $\Omega_{\text{photonic}} = 3 \times 10^{-5} \frac{T}{2.7K^0} 1/h_0^2$ where $H_0 = h_0$ 100 km/sec/MPC $\Omega_{\text{baryon}} \approx .014$

First hypothesis :

$\Omega_{DM} = \Omega_{\text{baryonic}} = .014$ (At most this could be pushed up to $\sim .15$. The limitation comes from the abundance of H^2, He^3, He^4, Li^7)

Baryonic Dark Matter it it exists could be in the form of:

1. White dwarfs
2. Neutron Stars
3. Black holes
4. Jupiters

Second hypothesis :

$\Omega_{DM} > \Omega_{\text{baryonic}}$;

At best one may motivate empirically, $\Omega_{\text{spiral galaxies} < 30\text{ MPC}} + \Omega_{\text{group of galaxies} < 30\text{ MPC}} = .2 \pm .1$

We must then assume that there is dark matter such that

$\Omega_{\text{smooth}} = .7 + .1$ to make up $\Omega_{\text{total}} = \Omega_{smooth} + \Omega_{\text{spiral galaxies}} = 1 \rightarrow$ respecting the inflationary hypothesis

---

TABLE 7

10. If Dark Matter Is Not Baryonic, What Is It?

"*Not only is man not the Centre of the universe physically (Copernicus) or biologically (Darwin) but* we and all we see *are not even made of the predominant matter variety in the universe.*"

Martin Rees

(If dark matter is not baryonic).

There are three classes of Dark Matter candidates, Hot, Warm and Cold:

10.1 HOT DARK MATTER PARTICLES (LIKE NEUTRINOS) STILL IN THERMAL EQUILIBRIUM:

1) Cosmological number density comparable to microwave background
$\Rightarrow$ i.e. mass $\approx$ few tens of eV;

2) *Fluctuation Spectrum.* The spectrum of fluctuations at late times in a hot dark matter model is controlled mainly by free streaming;

3) *Free streaming* destroys any fluctuation smaller than supercluster size. This gives top-down scale structure if dark matter is hot, i.e. galaxies and clusters form after superclusters;

(This is *not* the case for warm or cold dark matter.)

4) If $H_0 = h_0\ 100\ km/sec\ Mpc$;

$$\Sigma_\nu\ (1/2\ g_\nu) M_\nu \approx 100\ eV \frac{\rho}{\rho_c}\ h_0^{-2};$$

Thus, required neutrino mass,

$$M_\nu \sim (25 \text{ to } 100)\ \text{eV/species}.$$

Present experimental limits

$$M_{\nu_\tau} < 35\ MeV, \quad M_{\nu_\mu} < 250\ KeV,$$

$$M_{\nu_e} < 18\ eV(\text{Zurich}),\ \ 23\ eV(\text{Los Alamos}),\ \ 30\ eV(\text{Tokyo}),\ \ \approx 19\ eV(\text{ITEP})$$

from SN 1987a

$$M_{\nu_e} < 15 eV.$$

10.2 POTENTIAL PROBLEMS WITH *HOT* DARK MATTER

1) Galaxy formation presumably took place before $z = 3$. If QSOs are associated with galaxies, as suggested by galactic luminosity around nearby QSOs, abundance of QSO at $z > 2$ is inconsistent with "Top–Down" neutrino dominated scheme.

2) X-rays from the shock–heated pancakes are missing.

"These (serious) problems, however, may not be fatal for the hypothesis that neutrinos are the dark matter."

J. Primack

10.3 CANDIDATES FOR WARM DARK MATTER

1) Supersymmetric partners, like the light gravitino $M = M_{SUSY}^2 \; M_{pl}^{-1}$ (spontaneous SS breaking) so $M \approx 1 \; keV$ if $M_{SUSY} \approx 10^6 GeV$.

2) A hypothetical light right-handed neutrino ν_R (predicted, for example, by GUT SO(10)) could be a warm–dark matter candidate but Particle Physics provides no reason why ν_R should be light.

10.4 CANDIDATES FOR COLD DARK MATTER (The favourite model of particle physicists)

1. *Quark Nuggets* (Witten)

   i.e. Ultra Dense Matter with $\#u \sim \#d \sim \#s$

2. *Massive Neutrinos*

   Few GeV.

3. *Axions*

   Light scalar Goldstone bosons needed to conserve CP in strong nuclear interactions.

4. *Supersymmetric Relics*

   Lightest one (perhaps photinos of a few GeV in mass) expected to be stable due to the conservation of R quantum number (which in general = −1 for the new supersymmetric partners).

10.5 CONSTRAINTS ON AXION MODELS

1. Laboratory Experiments

   (axion $\rightarrow 2\gamma$, and assuming the # of axions $\approx 10^3$ times # photons)

   $f_a > 10^3$ GeV (where f_a is defined from the Lagrangian term $f_a^{-1} \; \phi_a \; F_{\mu\nu} \; \tilde{F}_{\mu\nu}$ and ϕ_a is the axion–field)

2. Standard Solar Model

   $f_a > 10^7$ GeV

3. Solar Axio – Electric Effect

   search in underground Ge detector (Ahlen et al.)

   $f_a > .5 \times 10^7$ GeV

4. Red Giants, White Dwarfs, Neutron Systems

   $f_a > 10^9$ GeV

5. Supernova 1987

   new limit $f_a > 10^{11}$ GeV

6. Cosmological Limit

   $f_a < 10^{12}$ GeV

   Thus the window on the axion is fast closing.

11. Cosmic Strings In Relation to TOE Strings

1. Any string produced before inflation is exponentially diluted.

2. Cosmic strings may be *superconducting*, large currents ($\approx 10^{20} A$) release energies $\approx 10^{60}$ ergs; trigger *explosive* galaxy formation.

3. "*It is argued that, in fundamental string theories, as one traces the universe back in time, a point is reached when the expansion rate is so fast, that the rate of string creation due to quantum effect balances the diluition of the string density due to the expansion. One is therefore led into a phase of constant string density and an exponentially expanding universe. Fundamental strings therefore seem to lead naturally to inflation.*"

Turok

12. Laboratory Tests For Dark Matter A.

1) Axion detectors $a \to 2\gamma$ in an inhomogeneous magnetic field find $m_a \leq 10^{-5}$ eV;

2) Bolometric detectors $\to$ with $\sigma_{scatt} \sim \sigma_{weak}$ deposit keV energies;

3) Monopole detectors (like the MACRO) in Gran Sasso (which is a truly impressive laboratory).

"Laboratory schemes for detecting a halo population of exotic particles most worthwhile and exciting high-risk experiment in Physics or Astrophysics (as important as the discovery of microwave background in the 1960s)."

M. Rees

Mean velocity of halo particles relative to the detector would have an *annual variation* (because of the earth's motion around the sun). The most important part of the test:

The variation in amplitude $\sim$ few % and peaking in June would provide *evidence against spurious background.*

B. A variety of detection principles such as superheated superconducting granules (SSG), bolometers, ballistic phonons, rotons in superfluid helium, transition edge thermometers and superconducting tunnel junctions have recently been (theoretically) investigated for SSG devices. Since the involved energy quanta for these detectors are so much smaller ($\sim 1/1000$ eV for breaking a Cooper pair in a superconductor for example) than for conventional ionisation (~ 20 eV) or semiconductor (~ 1 eV) detectors, in principle very low energy thresholds and very good energy resolution can be expected ...

"For solar neutrino detection, the coherent neutral current neutrino–nucleus scattering method is used. This method has the advantage that the cross-section is three orders of magnitude larger than the cross-section of other processes, like, for example, inverse beta–decay. Thus, an SSG detector with a weight of a few kilograms would measure the same event rate as a multi–ton detector based on other processes. The second advantage is that the SSG detector responds to all neutrino flavours equally."

K. Pretzl

in Particle Physics (Gonzalez–Mestres and Perret–Gallix,

	PRESENCE NEAR EARTH	ABUNDANCE	INTERACTION WITH MATTER	PROPOSED DETECTION TECHNIQUES
	COSMIC GALACTIC	$\Omega \sim 1$ if $5eV < m_\nu < 30eV$	COHERENT SCATTERING IF DIRAC MASS	??
	GALACTIC	$\Omega \sim 1$ if $m_a \sim 10^{-5}$ eV?	$a \to \gamma$ conversion in a strong emf.	LOW TEMPERATURE ELECTROMAGNETIC CAVITIES
	SOLAR	flux on earth: 10^5 to $10^{11} cm^{-2} s^{-1}$	$a \to \gamma$ conversion in atoms.	SILICON DIODES LOW TEMPERATURE DETECTORS
	GALACTIC	Eventually, $\Omega \sim 1$	WEAK (COHERENT IF DIRAC MASS)	IONIZATION DETECTORS FOR HEAVY PARTICLES
	GALACTIC	Eventually, $\Omega \sim 1$	SUPERSYMMETRIC (spin–dependent in most models)	LOW TEMPERATURE DETECTORS FOR ENERGY DEPOSITS BELOW 1 keV: SSG STJ Bolometers
eV	SOLAR and GALACTIC	$\Omega \sim 1$ possible	$\sigma \sim 10^2 \sigma_{weak}$	
	GALACTIC TRAPPED AROUND SUN	PARKER BOUND BOUNDS FROM RUBAKOV EFFECT	ELECTROMAGNETIC	CONVENTIONAL SUPERCONDUCTING
	GALACTIC	Eventually, $\Omega \sim 1$	ATOMIC COLLISIONS	ACCORDING TO MASS

TABLE 8

13. Envoi

I started this paper by speaking of the four standard models elaborated during this century. In closing I would like to mention how the biological standard model is being influenced by recent advances in particle physics.

It is well known that one of the basic problems in biology is the left– handedness of naturally occurring amino–acids and the right–handedness of sugars. In the laboratory these are produced as racemic mixtures with left and right molecules equal in numbers. (Thalidomide was one such laboratory racemic mixture which led to tragic results for the new–born babies.) A happier case is that of penicillin which splits open the D–type skins of bacteria.

In this respect it has recently been suggested (see, S. Mason, New Scientist, 19 January 1984, for a review) that a clue to a solution of this mystery may lie in electroweak unification and the appearance of the neutral (left– handed) weak interactions in the chemical Hamiltonian. This is shown to make for a small preponderance of left–handed amino–acids (and right–handed sugars) – 1 part in 10^{17}. This preponderance, plus the longevity of the biological epoch, *apparently* explain the occurrence in natural environment of the stated forms of chiral molecules.

14. Conclusions

14.1 OPEN QUESTIONS BEYOND THE STANDARD MODEL

PARTICLE PHYSICS

1. The status of the standard model? What lies beyond it, GUT or strings?
2. Are there supersymmetric particles?
3. The dark matter, does it exist? Its composition? Is it cold?
4. Are quarks & leptons composite? (not elementary at energies in excess of 1000 GeV)
5. Do gauge-bosons like W_R (mediating weak $V + A$) or $SU_A(3)$ (strong axial gluons) or string-inspired $Z^{0'}$ exist? likewise the existence of axions, familons, majorons at a new mass scale $\approx 10^{11}$ GeV. Are there present Goldstone particles?
6. q masses, their oscillations; Do ν_R exist? Solar ν puzzle? Is it a puzzle at all?
7. The near zeroness of the cosmological constant

14.2 OPEN PROBLEMS IN COSMOLOGY

1. The dark matter. Does it exist? Its composition?

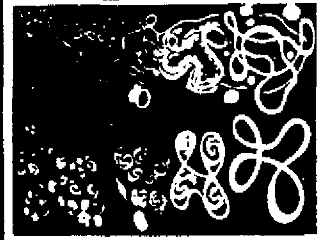
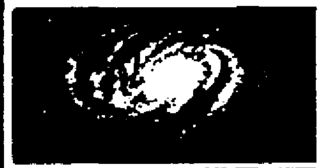
2. Photon-to-baryon ratio

Grand unification theories suggest that this ratio can be explained in terms of baryon non-conservation processes, and GUT parameters. Is that so?

3. Fluctuation spectrum $(\Delta\rho/\rho)$

4. The near zeroness of the cosmological constant.

The Powers of Ten

Measuring Instruments	Distance m.	Systems		Forces
Telescopes	10^{26}	Universe		Gravity
	10^{22}	Cosmic Strings Voids Supercluster of Galaxies Cluster of Galaxies		
	10^{19}	Galaxy		
	10^{12}	Solar System		
Eye	1	Man		Electromagnetism
Microscopes	10^{-8}	Molecule		
	10^{-10}	Atom		
				

I shall conclude this brief paper by repeating Glashow's picture of the Universe. This should show "generalized" gravity as it emerges from string theory as the Theory of Everything (T.O.E.) uniting all things "great and small".

I am indebted to John Ellis, Martin Rees, Dennis Sciama and Donald Lynden–Bell for help with cosmology.