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RECENT DEVELOPMENTS IN COSMOLOGY AND NUCLEOCHRONOMETRY*

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Cosmology is currently entering a new phase of comprehensiveness, precision and confidence. Recent developments in theoretical and observational cosmology (including accelerating expansion, cosmic microwave background anisotropy and nonzero-mass neutrino oscillations) and nucleochonometry are herein reviewed, presenting the latest values of quasar redshift, cosmological parameters in the standard model (with concentration upon the Hubble constant and the age of the Universe) and dating information from nuclear astrophysics. The methods and findings of nucleochronology, in the main based upon stellar r-process neutron capture rate data relevant to, *e.g.*, ^{137}Re/^{137}Os chronometry, Th/Eu abundance ratios and Th or U chronometry techniques are discussed in detail. Recent findings concerning the accelerated expansion of the Universe are presented, with consideration given to cosmological implications of, *e.g.*, dark energy, exotic dark matter, cosmic strings and supergravity. In conclusion, some remaining current problems and uncertainties are briefly noted.

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1. Introduction

Any approach to so grandiose a subject as the Universe, in all its evolutionary splendour and complexity, calls for a rich measure of diffidence and caution. Indeed, a recent warning has been sounded [1] against the tendency to draw very speculative inferences from the wealth of observational data now at our disposal, even though for most of its $\sim 10^{17}$-seconds lifetime

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since its birth at the Planck era (10^{-43} sec) up until the decoupling stage (at 10^{13} sec) it was opaque for 56 out of 60 logarithmic increments of time, defying direct observational scrutiny.

Acknowledging our (fortunate!) inability to initiate controlled experiments and interfere directly with the Universe but merely to observe and hypothesize and, moreover, recognizing our inability to penetrate beyond the observational horizons, limited in brightness, frequency, discrimination — and sheer serendipity — it behoves us to exercise circumspection in drawing inferences and claiming insights without adequate justification. The speed with which new data are being acquired, new cosmological models being refined and new insights gleaned renders publications outdated even before they are communicated in print (or via e-mail, especially useful being the "astro-ph" preprint archives available on the Web at `xxx.lanl.gov/abs/astro-ph/` and `arXiv.org/abs/astro-ph/`). To single out some of the latest reviews of this burgeoning subject from among an extensive selection, those by Rubakov [2], Turner and Tyson [3], Freedman [4] and Silk [5] merit perusal. Of recent textbooks that have been able to at least briefly touch upon some of the latest findings, those by Bergström and Goobar [6], Peacock [7], Harrison [8] and Livio [9], as well as various Workshop, School and Conference proceedings, *e.g.*, [10–17], deserve mention.

Without gainsaying the enormous advances (including the evidence for accelerating cosmic expansion [9, 18–21], anisotropy of the cosmic microwave background (CMB), as revealed by COBE (the COsmic Background Explorer [22–24]) and pending further more detailed exploration by MAP (the Microwave Background Probe, launched on June 30, 2001 to orbit the L2 point in order to provide fine-resolution detail of the CMB) and the implications of nonzero-mass neutrino oscillations [25, 26]; see also Refs. at this School) that have been made since last I enjoyed the privilege of reviewing the topic of cosmochronology and nucleochronometry [27] at this School a decade ago (at which time the Hubble Space Telescope, HST, had been in orbit for 1 1/2 years but was not then operational until the Servicing Mission in December 1993 remedied the spherical aberration in the primary WPC mirror), there is still much that is uncertain, more that is disputed, and yet more that remains to be established beyond reasonable doubt. And now there is even more ground to cover and a torrent of new results to consider!

2. Redshifts and the Universe

We see the Universe through rose-tinted glasses: much of what we infer about cosmological characteristics ensues from the interpretation of spectroscopic redshifts. It is instructive to contrast the latest progress with that, ten years ago, of my previous review [27]; see also [28]. The record redshift, defined as $z = \Delta\lambda/\lambda$, then stood at $z = 4.73$ for the quasar PC 1158+4635 (with a rumour [29] of an even higher value, $z = 4.9$); currently it stands [30–32] at $z = 6.28$ for the object designated, in terms of its coordinates, by the Sloan Digital Sky Survey collaboration, SDSS, as SDSSp J103027.10+052455.0. The generally-accepted range of values of the Hubble constant H_0 has effectively been narrowed from $H_0 \sim (50$ to $100)$ km s^{-1} Mpc^{-1} to between a low value [33, 34] of $H_0 = 58.5 \pm 6.3$ km s^{-1} Mpc^{-1} (which Tammann [35] rounds off to $H_0 = 60 \pm 6$ km s^{-1} Mpc^{-1} as the end-result of the Saha–Sandage–Tammann, SST, team) to a high value [36] of $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} (as the final result of the HST Key Project). This, for an idealized zero-density dustless Universe in which the redshift is given by the Special-Relativity Doppler formula $z = [(1+\beta)/(1-\beta)]^{1/2} - 1 = \gamma(1+\beta) - 1$, where $\gamma = (1-\beta^2)^{-1/2}$ and $\beta = v/c$, would imply a recessional velocity $v = 0.96\,c$ and a remoteness, according to Hubble's law $d = H_0/v$ with Hubble's constant taken as $H_0 = 58.5$ km s^{-1} Mpc^{-1}, of $d = 4.93$ Gpc = 16 Glyr (or $d = 4.0$ Gpc = 13 Glyr if $H_0 = 72$ km s^{-1} Mpc^{-1}). The figure of 16 Glyr for the span of the presently observable Universe (in space and time) represents a good current estimate, in conformity with other findings, to be discussed in the following sections. It is consonant with the distance $d \sim 12$ Glyr assigned [37] to the most distant X-ray galaxy cluster yet found ($z = 1.768$), the radio-emitting cluster 3C294 observed in a joint venture between the space-based Chandra X-ray Observatory satellite and the Very Large Telescope in Chile. (Incidentally, among recent developments is the identification for the first time, in March, 2001, of a so-called type-II quasar, CXOCDFS J033229.9-275106, as a distant X-ray source within the Chandra Deep-Field South region in Fornax). As Haiman and Loeb [38] indicate, the highest plausible redshift of luminous quasars is likely to be in the region of $z = 10$ (under the reasonable assumption that black holes more massive than a few billion solar masses were already assembled within the first Gyr of the Universe's existence after the Big Bang); this would yield a maximal span $d_{\max} = 5.04$ Gpc = 16.4 Glyr, and so a maximal age $t_{\max} \sim 17$ Gyr.

3. Cosmological parameters

The "standard model" of cosmology, based upon the Friedmann equation in GRT, entails a set of basic parameters to describe the present state of the Universe. These have been listed in the upper part of Table I, with representative numerical values for nine such parameters that constitute Trimble's [39] "personal selection" (very close to those agreed upon at the August 1997 meeting of the International Astronomical Union).

TABLE I

Values of the principal cosmological parameters.

Parameter	Symbol	Value	Ref.
Standard Model Parameters:			
Gravitational constant (Official Bureau International des Poids et Mesures)	G	(6.673 ± 0.010) $\times 10^{-11}$ kg^{-1} m^3 s^{-2}	
Scale parameter	R		
Spatial curvature parameter	k	($k = +1$: Positive curvature) ($k = 0$: Flat space) ($k = -1$: Negative curvature)	
		0	[39]
Hubble constant	$H = (1/R)(dR/dt)$		
Present-day Hubble constant	H_0	$100\ h$ km s^{-1} Mpc^{-1}	
		65 ± 15 km s^{-1} Mpc^{-1}	[39]
Hubble constant	$h = H_0/100$	0.65 ± 0.15	[39]
Deceleration parameter	$q = -(1/RH^2)(d^2R/dt^2)$	$0.0^{+0.2}_{-0.5}$	[39]
Critical density	$\rho_{\rm crit} = 3H_0^2/8\pi G$	$1.88 \times 10^{-26} h^2$ kg m^{-3}	
Density parameter	$\Omega = \rho/\rho_{\rm crit}$ $= (8/3)(\pi\rho G/H^2)$	($\Omega < 0$: Open Universe) ($\Omega = 0$: Flat Universe) ($\Omega > 0$: Closed Universe)	
Baryon density	Ω_b	0.04 ± 0.01 for $h = 0.65$	[39]
Matter density	Ω_m	0.3 ± 0.1	[39]
Vacuum energy density	Ω_Λ	0.65 ± 0.1	[39]
Cosmological constant	Λ	$\sim 10^{-35}$ s^{-2} (for $h = 0.65$)	[20]
Age of the Universe	t_0	14 ± 3 Gyr	[39]
Primordial lump spectrum	n	1.0 ± 0.2 (*i.e.*, simplest)	[39]
CMB temperature variation	$\Delta T/T$	$(2 \pm 0.5) \times 10^{-5}$	[39]
Current Cosmological Parameters:			
Gravitational constant	G	6.674215×10^{-11} kg^{-1} m^3 s^{-2}	[40]
		6.67559×10^{-11} kg^{-1} m^3 s^{-2}	[41]
Hubble constant (SST)	H_0	60 ± 6 km s^{-1} Mpc^{-1}	[35]
" (S-Z for MS 0451.6 & Cl 0016+16 with $z = 0.55$)		$63\ {}_{\rm r}\pm^{12}_{9}\ {}_{\rm s}\pm 21$	[42]
" (Key Project Collab.)		72 ± 8 km s^{-1} Mpc^{-1}	[36]
" (Cepheids: SN Ia 1991T in NGC 4527)		$73\ {}_{\rm r}\pm 2\ {}_{\rm s}\pm 7$	[43]
Hubble constant (my choice)	$h = 100/H_0$	0.6	
Total overall density	$\Omega_{\rm tot} = \rho/\rho_{\rm crit}$	1.0 ± 0.2	[44]
"		1.08 ± 0.06	[45]
"		$1.11\ {}_{\rm r}\pm 0.07\ {}_{\rm s}\pm 0.13$	[46]
"		$1.0 \pm 0.300.15$	[122]
Baryon density	Ω_b	0.045 ± 0.005	[44]
"		$(0.030 \pm 0.005)h^{-2}$	[45]
"		$(0.032\ {}_{\rm r}\pm 0.005\ {}_{\rm s}\pm 0.008)h^{-2}$	[46]
" (nucleosynthesis)		$(0.019 \pm 0.002)h^{-2}$	[45]
"		$(0.020 \pm 0.002)h^{-2}$	[47]
"		$(0.03 \pm 0.01)h^{-2}$	[122]
Matter density	Ω_m	$0.2 \pm 0.10.3$	[48]
" (High-z)		$0.4\pm^{0.5}_{0.4}$	[49]
" (CMB)		$0.28\ {}_{\rm r}\pm 0.09\ {}_{\rm s}\pm 0.05$	[20]
" (nucleosynthesis + X-ray)		$(0.25 \pm 0.02)h^{-1/2}$	[44]
" (nucleosynthesis + S-Z)		$(0.24 \pm 0.03)h^{-1}$	[44]
"		0.35 ± 0.15	[50]
"		0.16 ± 0.03	[51]
"		0.19 ± 0.03	[52]
Radiation density	$\Omega_{\gamma,\nu}$	$(4.17 \times 10^{-5})h^{-2}$	[3]
Neutrino density	Ω_ν	~ 0.007	[54]
Cold Dark Matter density	$\Omega_{\rm CDM}$	$(0.17 \pm 0.02)h^{-2}$	[45]
"		$(0.2\pm^{0.2}_{0.1})h^{-2}$	[122]
Vacuum energy density	Ω_Λ	0.7 ± 0.1	[20]
"		0.8 ± 0.2	[44]
"		0.66 ± 0.06	[45]
Most distant X-ray quasar	d	12 Glyr	[37]
Age of the oldest globular clusters	$t_{\rm GC}$	12.5 Gyr	[55]
Age of the oldest stars	t^*	13 ± 3 Gyr	[5]
Hubble time	$t_{\rm H} = 1/H_0$	$14.9 \pm^{1.4}_{1.1}$ $(0.63/h)$ Gyr	[20]
"		(SST): 15.7 Gyr	[34]
"		(Key Project): 13.6 Gyr	[36]
Age of the Universe (my choice)	t_0	$\sim 16\pm 3$ Gyr	

${}_{\rm r}\pm$ denotes random error; ${}_{\rm s}\pm$ denotes systematic error.

Meanwhile, refinements in the observational techniques and data reduction have provided improved values, which are listed in the lower part of Table I as the latest "accepted" results. These, and their derivation, will be discussed in the subsections which follow.

3.1. The distance scale, the Hubble constant and the age of the Universe

The Hubble constant represents the jewel in the crown of cosmology. Through its reciprocal, the "Hubble time", it sets the effective age and size of the observable Universe, when taken together with the density parameter Ω and the cosmological constant Λ. The square of the Hubble constant relates the total energy density of the Universe to its geometry [40, 41] and, when combined with the gravitational constant G, defines the critical density, ρ_{crit}. Moreover, a determination of many physical properties of galaxies and quasars (such as mass and luminosity, as well as energy density) entails a knowledge of H, as does also a measure of the proportion of primordial light elements (^{1}H, ^{2}D, ^{3,4}He, ^{7}Li) synthesized in the earliest stages of evolution. However, its determination in the main depends crucially upon a knowledge of the distance to astronomic objects, such as supernovae and variable stars in galactic clusters, as determined from "standard candles" of known intrinsic luminosity.

Primary among these "standard candles" are Type-Ia supernovae (SNae Ia) and Cepheid variables. SNae Ia outbursts (having spectra that exhibit strong absorption near 6150 Å, attributed to Si II) originate each time a (carbon–oxygen) white dwarf star's mass is carried over the Chandrasekhar limit by a mass-shedding companion. Thereby, the luminosity is essentially fixed to a definite value under effectively equivalent physical conditions, staying high and constant in time. However, such outbursts are comparatively seldom and unforeseeable in advance. Cepheids constitute the most important class of relatively high-mass (ranging from 3 to 20 solar masses) variable stars, undergoing regular characteristic pulsations of intensity, due to periodic expansion/contraction cycles in size, of periodicity ranging from 1 to more than 100 days (the prototype, δ Cephei, has a period $P = 5.37$ days). The period's strict relationship to luminosity L (and thence to the intrinsic brightness, represented by the absolute magnitude M) is embodied in the P–L relation, which in turn (after some corrections are applied for the effects of *e.g.*, dust absorption, reddening and metallicity) provides the "distance modulus," M–m, for the calibration of a distance scale when the observed brightness (the apparent magnitude m) has been determined and the absolute magnitude M deduced (from a variety of methods, to be described hereafter) The method was developed to high precision principally by Hubble (who in 1925 used it to deduce the presence of galaxies beyond our own) and Sandage. Understandably, Sandage and the SST team have played a leading role in harnessing it to the determination of the Hubble constant to arrive [34] at the aforementioned value, $H_0 = 58.5 \pm 6.3$ km s^{-1} Mpc^{-1}. If one admits an appreciable "dark-energy" density and uses the parameters $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ (corresponding to currently-adopted values for a flat universe with $\Omega_m + \Omega_\Lambda = 1$), the Hubble constant increases to $H_0 = 60.9 \pm 2.0$ km s^{-1} Mpc^{-1}, as shown by Parodi, Saha, Sandage and Tammann [34, 55]. The other principal group of investigators, the HST Key Project collaboration, deduced [36] the somewhat higher value, $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1}, by using a calibration through Cepheids that relies predominantly on long-period variables that are most affected by the P–L relation as proposed by Udalski *et al.* [56]. We note in passing that the SST value for SNae Ia would be raised [35] to about $H_0 = 67$ km s^{-1} Mpc^{-1}, closely compatible with the Key Project value, if the P–L relation of Udalski *et al.* were used together with the somewhat low Cepheid distances proposed by Gibson *et al.* [57] of the Key Project group (leading to a diminution in the distance modulus for SNae Ia by 0.29 magnitudes, or by only 0.23 magnitudes if the metallicity corrections of the Key group [36] are employed). The SNae Ia approach can be used for distance determinations out to about 400 Mpc, currently the highest remoteness measurable except for gravitational-lensing methods.

The different selections of SNae Ia and Cepheids, as well as the different correction procedures adopted by the different groups in each of the different methods accordingly led to different end-results, as indicated in Table II. The SST group demonstrated (in their Fig. 1 of Ref. [34]) that their choice of 35 SNae Ia in the recession-velocity ("Hubble-flow", *i.e.,* distance) range $v = 1.2$–30 Mm/sec with reliably known, nonpeculiar B and V magnitudes m at maximum light provided an excellent fit to the Hubble diagram, of log*(v) versus* corrected apparent magnitude, $m_{\max}$. Of these, the 29-member subset with "good" infrared $I_{\max}$ corrected magnitudes yielded a similarly excellent match, with hardly any scatter from linearity. The B, V, I slopes s_λ and intercepts c_λ likewise matched closely for each λ-passband. With M_λ the absolute magnitude in each case, the value of the Hubble constant could be derived from the relation

$$\log(H_0) = s_\lambda M_\lambda + c_\lambda + 5\,. \tag{1}$$

In applying this to the acquired data, it is necessary only to measure M_λ for one (or, in practice, a few) *nearby* SNae Ia. This luminosity calibration, effected with the aid of the P–L relation for Large Magellanic Cloud (LMC) Cepheids with the distance modulus taken as the conventional value $(m\text{–}M)_{\rm LMC} = 18.50$, led (for a critical-density flat Universe with $\Omega_m = 1$, $\Omega_\Lambda = 0$) to

$$
\begin{aligned}
H_0(B) &= 60.3 \pm 2.0\,,\\
H_0(V) &= 60.1{\pm}1.8 \quad \text{and}\\
H_0(I) &= 60.0{\pm}2.8 \quad \text{km s}^{-1}\text{Mpc}^{-1}\,,
\end{aligned}
$$

or, when adjusted for the currently favoured parameter choice ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$) to a mean value [55]

$$H_0 = 60.9{\pm}2.0 \quad \text{km s}^{-1}\text{Mpc}^{-1}\,.$$

TABLE II

Numbers of supernovae and Cepheids used for determination of the Hubble constant and Hubble time.

Group [Ref.]	Secondary technique	Number	Hubble constant H_0 (km s^{-1} Mpc^{-1})	Hubble time $1/H_0$ (Gyr)
SST [33,34]	Type Ia supernovae (SNae Ia)	35	61 ± 2	16.0
	Clusters of galaxies	72	51 ± 6	19.1
	Tully–Fisher relation (T–F relation)	21	63 ± 5	15.5
	Other methods (Virgo distance)	31	56 ± 8	17.5
	Other methods (Coma distance)	10	66 ± 8	14.8
	Mean		59 ± 3	16.6
[35]	**Combined (Tammann priv. comm.)**		60 ± 6	16.3
Key [35]	Type Ia supernovae (SNae Ia)	36	$71\ {}_{\rm r}{\pm}2\ {}_{\rm s}{\pm}6$	13.8
	Tully–Fisher relation (T–F relation)	21	$71\ {}_{\rm r}{\pm}3\ {}_{\rm s}{\pm}7$	13.8
	Fundamental Plane (FP method)	11	$82\ {}_{\rm r}{\pm}6\ {}_{\rm s}{\pm}9$	11.9
	Surface Brightness Fluctuations (SBF)	6	$70\ {}_{\rm r}{\pm}5\ {}_{\rm s}{\pm}6$	14.0
	Type II supernovae (SNae II)	4	$72\ {}_{\rm r}{\pm}9\ {}_{\rm s}{\pm}7$	13.6
	Combined (Monte Carlo)		$72\ {}_{\rm r}{\pm}3$	13.6

${}_{\rm r}{\pm}$ denotes random error; ${}_{\rm s}{\pm}$ denotes systematic error.

The Key Project [36] group, on the other hand, studied 36 SNae Ia and independently derived Cepheid distances to 7 galaxies that were hosts to SNae Ia. This led to their revising the distance scale and recalibrating the P–L relation, thereby obtaining as a final result

$$H_0 = 71\ {}_{\rm r}{\pm}2\ {}_{\rm s}{\pm}6 \quad \text{km}\,\text{s}^{-1}\text{Mpc}^{-1}\,.$$

Another method, pioneered in 1973 by Sandage and Hardy [58], uses first-ranked cluster galaxies as standard candles. The SST group employed this for a set of 72 objects having v = 3.5–30 Mm/sec and introduced further refinements to the basic technique. However, inherent to this approach is an accurate knowledge of the distance to, *e.g.,* the Virgo, Fornax and/or Coma cluster of galaxies. With this aim, a separate investigation was mounted, making use of the Tully–Fisher (T–F) relation [59], which is suited for distance determination of *spiral* galaxies out to intermediate distances ($d \sim$ 150 Mpc).

The T–F relation for the measurement of extragalactic distances rests upon the fact that the total luminosity (corrected for face-on inclination) correlates strongly with the maximum rotation velocity of the galaxy. The latest findings are listed in Table II for the SST and Key Project groups; further details and the latest references are to be found in their reports [34,36].

Akin to the situation for *spiral* galaxies, in which the intrinsic luminosity is related to their rotational velocity in the T–F relation, for *elliptical* galaxies there is a comparable relation between luminosity and the stellar *velocity dispersion* in the cluster. Faber and Jackson [60] introduced a so-called Fundamental Plane (FP), wherein a defined "effective" radius $r_{\rm eff}$ for a given elliptical galaxy is strongly correlated with the surface brightness $I(r_{\rm eff})$ within that radius and the central velocity dispersion of that galaxy. The fundamental plane for early-type elliptical galaxies in 11 clusters with v = 1–11 Mm/sec has been studied by Jørgensen, Franx and Kjaergaard [61]; the results have been combined with revised distance and metallicity calibrations by the Key Project group (as the fundamental plane method is particularly susceptible to such recalibration), to obtain the overall rather high value of the Hubble constant [35],

$$H_0 = 82\ {}_{\rm r}{\pm}6\ {}_{\rm s}{\pm}9\ {\rm km\,s^{-1}Mpc^{-1}}$$

cited in Table II (with ${}_{\rm r}\pm$ denoting random error and ${}_{\rm s}\pm$ denoting systematic error). The ensuing rather short Hubble time, $t_{\rm H} = 1/H_0 = 11.9$ Gyr, is open to dispute, as the intrinsic errors in this method may be appreciably higher than those in other techniques.

Higher internal precision is offered by the method of studying Surface Brightness Fluctuations (SBF) developed by Tonry and Schneider [62], and Tonry *et al.* [63, 64] for *spiral and elliptical galaxies* having a prominent central bulge. The underlying principle rests upon the fact that the resolution of stars within galaxies is distance dependent. By normalizing to the mean total flux, and correcting for the observed colour dependence, relative distances to galaxies can be measured and a calibration scale derived. So far, only 6 clusters, within the narrow range v = 3.8–5.8 Mm/sec (in which local flow velocities are appreciable), have proved suitable for precision analysis, as listed in Table II, but further investigations which are currently underway hold considerable promise for this technique. A procedure for extracting a synthesis of data from FP and SBF surveys has latterly been put forward by Blakeslee *et al.* [65].

Alternatively, when restricted to age studies of stars solely in our Milky Way (MW) galaxy, two powerful methods have been developed, based upon models of stellar evolution, which at the very least provide a reliable indication of a lower limit. Regarding metal-poor halo stars or globular clusters as the oldest objects in our MW galaxy, Chaboyer, Demarque, Kernan and Krauss [66] carried out an investigation of the 17 oldest globular clusters with stellar evolution codes, taking into account observational uncertainties in the absolute magnitudes M of RR Lyrae variable stars to obtain a probability distribution for the mean age of these systems. The lower bound for the distribution (with 95% confidence) proved to be 12.07 Gyr, the median being 14.56 Gyr. This figure was subsequently revised to $t_{\rm halo} = 11.5 \pm 1.3$ Gyr by Chaboyer [67] on basing his estimate upon the absolute magnitude of the main-sequence turn-off in globular clusters in the Herzsprung–Russell diagram, again making use of more refined stellar evolution models. A yet more recently revised value for halo globular-cluster mean age has been cited as $t_{\rm halo} = 12.8 \pm 1$ Gyr by Krauss [68], which compares well with post-HIPPARCOS corrected ages of $t_{\rm halo} = 12 \pm 1$ Gyr and $t_{\rm halo} = 11.8 \pm 1.2$ Gyr derived respectively by Reid [69] and Gratton *et al.* [70] from main-sequence fitting analyses.

In an ancillary study by Oswalt *et al.* [71] of white-dwarf cooling ages (determined from their luminosities in a sample of the faintest local white dwarfs at the end of their evolutionary sequence) an age for MW *local disk* stars was derived as $t_{\rm disk} = 9.5_{-0.8}{}^{+1.1}$ Gyr. Again, this constitutes essentially a *lower limit*, applicable solely to our own galaxy rather than to the ensemble of galaxies in the Universe proper. For these, a broader view is needed.

One such endeavour currently being vigorously pursued involves studies with type-II supernovae (SNae II). These are distinguished from type-I SNae (whose optical spectra are hydrogen-deficient) by the marked presence of H lines in their spectra. They cannot be regarded as true “standard candles” as their luminosities vary over an appreciably wider range than those of SNae Ia (and they are considerably fainter), but their outbursts (from core collapse of massive supergiant stars) yield expanding atmospheres whose spectral time evolution can, with the aid of the Baade–Wesselink technique, provide an indication of distance. The method is still in its developmental stage, an interim result being listed in Table II. Indeed, even the light echo of a supernova outburst observed in the surrounding interstellar medium offers the potential to measure the Hubble constant, as suggested by Sparks *et al.* [72, 73]. If the position and the time of maximum polarization can be determined, the distance can be derived from the geometry. Due to the rapid dimming of the echo's surface brightness, the method is feasible only with the superior resolving power of the HST and probably cannot extend out to the $v > 5$ Mm/sec remoteness desirable for a large-scale measurement of H_0. In connection with the peculiar type-II supernova SN 1987A in the LMC, it bears mentioning that an adjustment to the distance modulus $(M\text{–}m)_{\mathrm{LMC}}$ of the Large Magellanic Cloud to 18.58 ± 0.05 (from its conventional value of 18.50) was proposed by Panagia [74] from a *geometric distance* measurement of the fluorescent ring around SN 1987A from observations with the International Ultraviolet Explorer (IUE) and the HST. One notes also that some augmentation of the conventional value is indicated from calibrations of galactic Cepheids with the astrometric satellite HIPPARCOS, which also suggest a somewhat larger distance to the LMC.

Gravitational-lensing and Einstein-ring effects also offer possibilities for inferring galactic distances and the Hubble constant. So far, only one application has been attempted, in which Kochanek, Keeton and McLeod [75] set an upper limit, $H_0 < 60$ km s^{-1} Mpc^{-1}, from observations of the quasar PG 1115+080, imaged fourfold. In this method, once the geometric configuration has been reconstructed, the particulars can be calibrated by the time delay between the light curves of the individual images to provide absolute distances, without any need to refer to Cepheids or any other variables. Such gravitational lensing offers attractive prospects for the elucidation of H_0, Ω and Λ, in addition to other cosmological details, but the technique is yet in its early stages and calls for further investigation and refinement.

The Cosmic Microwave Background (CMB), *i.e.,* the "relic radiation" that originated some 300,000 years after the Big Bang during the decoupling era when the Universe first became transparent and that represents the earliest measurable constituent of the Universe also offers immense possibilities for cosmological enquiry. The all-pervading CMB radiation, now cooled from its initial 3,000 K to the present 2.7277 ± 0.002 K, is almost perfectly isotropic, with deviations from a Planckian spectrum smaller than 300 parts per million [76]. Anisotropies were first detected a decade ago with the Differential Microwave Radiometer (DMR) of the Cosmic Background Explorer (COBE) satellite [22–24]; including measurements with the Far InfraRed Absolute Spectrophotometer (FIRAS) on this satellite, a review of the COBE findings has been presented by Page and Wilkinson [77], indicating among other data that the barycentre of the solar system has a velocity of 370 ± 0.5 km/sec. Taking into account our motion around the centre of our Milky Way galaxy, this translates to a motion of 620 ± 20 km/sec for our local group of galaxies. A recent summary of current measurements of the power spectrum of CMB temperature variations for several experiments has been shown in a figure (courtesy of M. Tegmark) that clearly displays the first (meanwhile extended also to the second and third [78]) acoustic peak (as evidence for a flat Universe with $\Omega_m = 0.35$ and hence $\Omega_\Lambda \sim 0.65$) in the cosmology review by Turner and Tyson [3]. These most recent studies, to be discussed later, also feature data from the BOOMERANG-98 (acronym for Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics) and MAXIMA-1 (Millimeter Anisotropy eXperIMent) balloon experiments. A discussion of the prospects for constraining cosmology with the extragalactic CMB temperature has recently been presented by LoSecco, Mathews and Wang [79], indicating that the current measurement uncertainty ($\Delta T = \pm 0.002$ K) in the local CMB temperature imposes intrinsic limits on the use of such measurements as a cosmological probe.

The COBE data, combined with X-ray data acquired by, *e.g.,* the Röntgen satellite (ROSAT), can also yield information via analysis of the Sunyaev–Zel'dovich (S–Z) effect [80,81] on the Hubble constant H_0 and evolution/age characteristics of galaxy clusters that are also X-ray emitters. The S–Z effect betokens a slight distortion of the CMB spectrum (a decrease at frequencies below 218 GHz and an increase above 218 GHz, occasioning a fractional decrement in intensity at radio frequencies of order 10^{-4}) due to inverse Compton scattering of CMB photons off the electrons in the hot (~ 10 keV) intercluster gas. In Table I is included the result obtained with this method by Reese *et al.* [42] for the two galactic clusters MS 0451.6-0305 and Cl 0016+16 at $z = 0.55$, namely $H_0 = 63\ {}_r\pm\ {}_9{}^{12}\ {}_s\pm\ 21$ km s^{-1} Mpc^{-1} (where ${}_r\pm$ represents the random error and ${}_s\pm$ the statistical error). A still more recent result is that by Mason, Myers and Readhead [74] for five galaxy clusters in flat cosmology, giving $\Omega_m = 0.35 \pm 0.05$ in a standard Cold Dark Matter (ΛCDM) model: $H_0 = 66\ {}_r\pm\ {}_{11}{}^{14}\ {}_s\pm\ 15$ km s^{-1} Mpc^{-1}.

With brief mention of the suggestion by Herrnstein *et al.* [82] that geometric measurements to deduce the distance to H_2O masers orbiting a supermassive nucleus (presumed to be a black hole) in the gas within an active galaxy (NGC 4258) — there are currently about 20 such cases — might yield a determination of H_0 as a by-product, we conclude this subsection and pass on to a consideration of nucleochronology as a determinant of age and evolution.

4. Nucleochronometry and nucleochronology

Just as the survey in the previous section supplements and updates that presented a decade ago at this School [27], so does the overview in this "nuclear-astrophysics" section complement that reviewed then, when the subject was barely out of its infancy. The use of nuclear methods for age determination has now reached a degree of sophistication that might be deemed to have matured to adolescence in dating and is still growing apace.

Attention is now in the main being directed to studies of nucleosynthesis by slow *(s-process)* or rapid *(r-process)* neutron capture in the early Universe to form long-lived radioactively-unstable isotopes, followed by their decay to stable nuclides. In the s-process, bombardment of the target nucleus by a moderate flux of free neutrons is sufficiently slow that almost any possible β-decays of the product neutron-rich nuclei have time enough to occur between successive neutron captures. The s-process nucleosynthesis generally occurs in helium fusion zones during the *late* quiescent stages of stellar evolution, consequently leading to an *under*-estimate of the evolution age. By contrast, in the r-process large neutron fluxes overwhelm the β-decay transition rates and thereby feed the nuclear isotopes out toward the "neutron drip line" in a matter of seconds, which thereafter gradually decay back toward the valley of β-stability after the neutron blast has terminated. There is still some dispute about the site and details of r-process nucleosynthesis; of the leading suggestions, namely (*i*) neutrino-driven winds from forming neutron stars, (*ii*) magnetic jets from collapsing stellar cores, (*iii*) decompression of cold neutron matter from neutron star mergers, and (*iv*) evolution of massive stars and SNae II, the two last-named currently seem to be the most viable. Cowan *et al.* [84] provide a more explicit discussion and recent references. In the selection of nuclides for nucleochronometry, it is those long-lived (half-life $t_{1/2} \sim$ Gyr) radioactive species formed via the r-process which have the most suitable characteristics. Of these, ^{187}Re ($t_{1/2}$ = 43.5 Gyr), ^{232}Th ($t_{1/2}$ = 14.05 Gyr), ^{235}U ($t_{1/2}$= 0.7038 Gyr), and ^{238}U ($t_{1/2}$ = 4.468 Gyr) clearly constitute the most favourable candidates while others, such as ^{40}K ($t_{1/2}$ = 1.277 Gyr), ^{87}Rb ($t_{1/2}$ = 47.5 Gyr), ^{138}La ($t_{1/2}$ = 105 Gyr) and ^{147}Sm ($t_{1/2}$ = 106 Gyr) are ruled out by a combination of factors, *e.g.*, details of their nucleosynthesis are at present not sufficiently well established, their spectra evince prohibitive complications and/or the half-life is inordinately long.

4.1. ^{187}Re nucleochronometry

Of the above, $^{187}{}_{75}$Re is at the upper end of the acceptable half-life range and has the added complication that the stable end-product of its β^- decay, $^{187}{}_{76}$Os, is also produced via an ancillary non-radiogenic neutron-capture s-process; moreover, the β-decay rate of ^{187}Re in stellar environments is rather acutely sensitive to temperature (in hot stars, the atomic orbitals open up due to ionization, and consequently the half-life is significantly reduced). The nuclear astrophysics has been studied by, *e.g.*, Yokoi, Takahashi and Arnould [85, 86], who deduced that the method indicates the age of the MW galaxy to lie within the range t_{MW} = 11–15 Gyr. Subsequent analyses by Meyer and Schramm [87] vindicated the use of ^{187}Re as a reliable chronometer despite its astration, but in recognition of the inherent uncertainties offered only an upper (model-independent) limit to the age of the galaxy ($t_{\mathrm{MW}} < 28.1$ Gyr) derived therefrom. In a later paper, Clayton [88] deduced an age-range $t_{\mathrm{MW}} = 14$–20 Gyr (an interesting sidelight is the fact that the original suggestion for ^{187}Re chronometry stemmed from Clayton [89] in 1964). Although the method has considerable potential and deserves greater attention in the future, its intrinsic difficulties have tended lately to sidestep its application in favour of Th and U nucleochronometry.

4.2. Th nucleochronometry

The 14-Gyr half-life of ^{232}Th also places it at the high end of the range of suitability for nucleochronometry (whereas ^{238}U, with $t_{1/2} = 4.468$ Gyr is, admittedly, more suitable in this respect), but nevertheless it has yielded excellent results, which complement and closely match those that ensue from uranium chronometry (discussed in Section 4.3). Early studies of stellar thorium chronometry based upon $_{90}$Th/$_{60}$Nd abundances as determined from spectral analyses was undertaken in 1987 by Butcher [90] and followed up by Morell *et al.* [91]. However, the use of neodymium as comparison element is handicapped by several factors, chief among them being the fact that its solar-system nucleosynthesis entails s- and r-process involvement in roughly equal measure. The replacement of $_{60}$Nd by $_{63}$Eu (a 97% r-process stable element in solar-system synthesis) is due to Pagel [92] and François *et al.* [93], who suggested comparing relative Th/Eu stellar abundances with solar abundances. With the determination by Sneden *et al.* [94] of the thorium abundance in the extremely metal-deficient halo field star CS 22892-052 and its ratio to europium, the program of thorium-dating acquired a momentum of its own. The theoretical r-process abundance ratio of Th/Eu = 0.51 served as the basis for such analyses (a recent compilation of r-process abundances and chronometers in metal-poor stars has been assembled by Cowan *et al.* [95]). From observations of the singly-ionized thorium 4019.12 Å line in this star Sneden *et al.* deduced a lower limit to the age as $t_{\mathrm{CS22892-052}} = 15.2 \pm 3.4$ Gyr. Subsequently, Westin *et al.* [96] measured the thorium abundance for another highly metal-deficient star, HD 115444, using theoretical predictions for production of Th and the stable elements via the r-process; on combining the age predictions for both these stars they obtained an *average* age as $t_* = 15.6 \pm 4.6$ Gyr [95, 96]. With their model and analysis, Westin *et al.* (cited by Truran *et al.* [97]) determined the ages of an additional four somewhat less metal-deficient stars (HD 186478, HD 108577, BD +8°2548 and M92 VII-18) as 18.9, 10.1, 9.4 and 9.4 Gyr, respectively. These findings may be compared with the respective values (18.3, 9.8, 8.9 and 8.8 Gyr) derived (as also 11.2 Gyr for HD 115444) as

"Case 4" results by Johnson and Bolte [98] from a different analytic procedure. Furthermore, in the listing by Truran, Blinkes, Cowan and Sneden [97] are included the two newer values by Sneden *et al.* [99] for CS 22892-052 and HD 11544 (as 16.8 and 14.4 Gyr, respectively), together with two results for stars K341 and K462 in M15, the globular cluster in Pegasus, namely $t_{\mathrm{K341}} = 14.4$ Gyr and $t_{\mathrm{K462}} = 16.8$ Gyr, attributed to Johnson and Bolte [98]. It also bears mentioning that Carretta *et al.* [100] estimated the age of M92, a globular cluster in Hercules, as 12.5 Gyr based upon main-sequence turn-off data. This is closely comparable with the *average* age of 14.5 ± 2 Gyr which Sneden *et al.* [101] recently obtained for three stars in the Pegasus globular cluster M15.

Although other potentially possible chronological combinations, such as Th/La or Th/Pt, have been suggested, the Th/Eu abundance method for age-determination of stars in our galaxy is at present the most viable. It has reached a satisfactory stage of reliability, though some aspects still invite refinement, particularly in respect of the derivation of time-zero relative abundances and in the analysis of spectroscopic features (a critique of uncertainties in Th cosmochronometry as of 1999 was published by Goriely and Clerbaux [102]). Currently, a spate of publications, *e.g.,* [103, 104, 105], provides a wealth of details and updates to the observations and the procedures employed in this burgeoning field of investigation.

The Th/Eu method has largely superseded the chronometry technique studying the parent/daughter ^{232}Th/^{238}U pair which was described in the previous review [27] and which has, to all intents and purposes, not been developed further meanwhile although it still offers interesting opportunities, deserving of further attention.

4.3. U nucleochronometry

The Th/Eu abundances in the preceding method required comparison of the *stellar* abundance with the *solar* abundance and extrapolation to the formation era. In the case of uranium, however, this has not hitherto been feasible since relative ^{238}U abundances were not known until very recently for any star other than the Sun. With the identification by Cayrel *et al.* [107] earlier this year of a weak absorption line at 3859.5 Å due to singly-ionized ^{238}U in the near-ultraviolet spectrum of the faint (magnitude $m_V = 11.7$) very metal-poor star CS 31082-001, an age determination along similar lines became possible. Using the new high-resolution resources of the UVES spectrograph at the European Southern Observatory (ESO) Very Large Telescope (VLT) in Chile, the group was able in addition to this U II line to detect fourteen ^{232}Th lines (including the 4019.12 Å Th II line and ten additional lines which appear to be first detections), as well as prominent

Os and Ir lines, which served in the derivation of U abundance ratios. By combining these with r-process production ratios, they were able to deduce the age of the halo field star: with the U/Th production ratio of Goriely and Clerbaux [102] as 14.0 ± 3.3 Gyr, whereas using that of Cowan *et al.* [95] they arrived at an appreciably lower age (10.6 ± 3.3 Gyr). For U/Os the age resulted as 13.6 ± 2.7 Gyr, while for U/Ir the age ensued as 11.8 ± 2.5 Gyr (again using the production data of Cowan *et al.* [95]). Stating that "Any age between 11.1 and 13.9 Gyr is compatible with the various determinations associated with their error bars", the authors take the median value 12.5 ± 3 Gyr as the best present estimate for the age of CS 31082-001.

This is in excellent accord with the radiometric age of 12.6 ± 2.6 Gyr cited in the previous survey [27] for the result of the ^{235}U/^{238}U analyses. It also tallies closely with findings by Rich [108] for the old stellar population of the central bulge in our MW galaxy and with the 13-Gyr age of 47 Tucanae, obtained from recent HST/NICMOS data.

It is noteworthy, too, that the ESO-VLT/UVES spectroscopy by Cayrel *et al.* [107] did *not* detect any U II line in the stars HD 115444 or HD 122563 featured in the Th/Eu dating, even though it has atmospheric parameters and an iron abundance closely similar to those of CS 31082-001. Intensive high-resolution searches are underway in the spectroscopy of HD 115444 and CS 22892-052, as well as other metal-poor stars in the halo (and the bulge) of the MW galaxy.

If one admits of other mixed r-/s-processes in nucleochronometry, then the suggestion of Cowan, Thielemann and Truran [109], proposing ^{206}Pb/^{238}U or ^{207}Pb/^{235}U dating studies bears consideration, as would also [110, 111] the pure s-process pair ^{176}Lu/^{176}Hf, albeit complicated by branching and temperature-sensitivity. With the present pace of progress in this field, developments can be anticipated on an almost weekly basis: any review such as this rapidly becomes outdated. In this Golden Age of cosmology, new data, observations, discoveries and ideas follow so rapidly upon one another that, at best, one can endeavour only to keep up with current trends. In the following section, an attempt to sketch the present status by way of a cursory overview is presented.

5. Recent developments and trends in cosmology

5.1. The Cosmic Microwave Background (CMB), anisotropy, inflation and reionization

Observational data in the earliest history of the Universe can be gleaned only from the time of the decoupling epoch (some 300,000 years after the Big Bang) when the relic radiation separated from the matter content and followed its own evolutionary path to become the present Cosmic Microwave

Background (CMB). The identification of anisotropy (at the 10° angular resolution level) in the current CMB from the COsmic Background Explorer (COBE) satellite's half-dozen Differential Microwave Radiometers (DMR) provided the incontrovertible evidence of structure [22–24], supporting adiabatic inflationary models [112, 113] for the generation and growth of density fluctuations in the early Universe [114–117].

Such density fluctuations manifest themselves as minute fluctuations in the differential temperature and (albeit only at considerably finer resolution) are able to provide vital information on the plasma characteristics of the early Universe in the train of inflation, as well as discriminating between inflationary models and determining the curvature of the Universe. The plasma oscillations of the CMB resemble soundlike "throbbing" of compressional/rarefactional waves in power; consequently the power spectrum, translated in terms of a spherical-harmonic series, displays a sequence of "acoustic peaks" in a plot of the squared harmonic coefficients *versus* the multipole order l. These are a measure of the mean square spatial temperature fluctuation ("variance") at angular separations near $180°/l$. As the angular resolution grows ever-finer, the standard inflationary scenario requires a pattern of ever-diminishing acoustic peaks. The 10° resolution of COBE lacked the finesse to show this pattern clearly, and even when supplemented by later data from balloon observations of the CMB was able to display only the first peak with hints of a second peak (appreciably lower than expected). The latter 1998 balloon launches were BOOMERANG-98, launched from the McMurdo site at the South Pole [118, 119], and MAXIMA-1, launched from the US National Scientific Balloon Facility at Palestine, Texas [120]. Subsequent expanded analysis [121] of the BOOMERANG-98 data showed better traces of the acoustic peaks at $l = 210$, 540 and 840 and produced an essentially unchanged (but improved) result for the baryon density, $\Omega_b = (0.022 \pm 0.004)h^{-2}$, yielding a total density $\Omega_{\mathrm{tot}} = 1.02 \pm 0.06$. Likewise, a high-resolution reanalysis of the MAXIMA-1 measurements by Stompor *et al.* [122], combined with COBE-DMR data, provided similar results, namely $\Omega_b = (0.0325 \pm 0.0125)h^{-2}$ and $\Omega_{\mathrm{tot}} = 0.9 \pm 0.17$. In this connection, mention should also be made of the constraints and findings from MAXIMA-1 data on cosmological data in the analysis by Balbi *et al.* [123], who determined $\Omega_b = (0.03 \pm 0.01)h^{-2}$ and $\Omega_{\mathrm{tot}} = 1.0_{-0.30}{}^{+0.15}$, together with a density of cold dark matter of $\Omega_{\mathrm{CDM}} = (0.2_{-0.1}{}^{+0.2})h^{-2}$; moreover, at the 95% confidence level they determined limits for the matter density and Λ-density respectively as $\Omega_m = 0.25$–0.50 and $\Omega_\Lambda = 0.45$–0.75. Attention is also drawn to the recent paper by Kaplinght and Turner [124] dealing with the latest developments in precision cosmology as they pertain to the density of baryons in the Universe.

With these more-stringently analyzed measurements, augmented by further data from the ground-based DASI (Degree Angular Scale Interferometer) at the South Pole [125, 126] the harmonic power spectrum, extending from $l \sim 100$–900, displayed a yet more convincing series of first, second and third acoustic peaks. To augment the studies of these CMB anisotropy experiments currently in progress, two satellite missions are now underway: namely, NASA's Microwave Anisotropy Probe (MAP) [127], launched successfully on June 30 for location at the fixed L2 Lagrangian point, 1.5 Gm antiskyward from Earth, describing Lissajous orbits. MAP has dual microwave dishes, capable of angular resolution from 13 arcmin to 1° at frequencies ranging from 22 to 90 GHz. This, together with the European Space Agency's Planck project [128], due for launch in 2007, will allow the power spectrum to be determined with highest precision to extend well beyond $l = 1000$.

Before going on to discuss the findings and implications in greater detail, it is interesting to note the observation of Miller *et al.* [129] that the first acoustic peak, localized to $l = 216 \pm 14$, was already evident in the data of the balloon-borne QMAP experiment combined with the Cerro Toco, Chile MAT/TOCO ground-based (5200-m altitude!) measurements and places constraints [79] upon sustainable cosmological parameters (as indicated in Table I).

As stated, the evidence strongly substantiates [46] a flat-Universe model. As Linde [112] points out, far from necessarily forcing the Universe to be homogeneous throughout, even on the largest scales, inflation as now visualized can produce *local homogeneity but, on the broadest scales, pronounced inhomogeneity*! In the simplest versions of inflationary theory, the Universe is regarded, not as a single exploding ball produced in the Big Bang, but rather in a fractal sense as many inflating, expanding balls, which in turn produce new balls, *ad infinitum.* Our own observable Universe constitutes but one of these bubbles, in which the brief ($\sim 10^{-32}$ sec) inflationary period of exponential expansion by a factor of more than 10^{26} smoothed out the original inhomogeneities by a factor of $10^{1,000,000,000,000}$ but which nonetheless still manifests a bubble structure in the large-scale distribution of astronomic objects. This is evident in the "Great Wall" and "Stickman" features identified in the Geller–Huchra survey [130] and, with ever-increasing clarity, in the three-dimentional SDSS deep-field 2dF Survey [30] which up to the present has assembled precision measurements of some 14 million astronomic objects (including the detailed spectra of 50,000 galaxies and 5,000 quasars, its ultimate goal extending to 100,000 quasars). A paper by Percival *et al.* [131] indicates that the 2dF Galaxy Redshift Survey has now measured in excess of 160,000 redshifts; analysis of the power spectrum of the galaxy distribution yielded values at 68% confidence limits of the matter density as $\Omega_m =$

$(0.20 \pm 0.03)h^{-1}$ and of the "baryon fraction" as $\Omega_b / \Omega_m = 0.15 \pm 0.07$, assuming scale-invariant primordial fluctuations.

The quantum process of particle creation in a self-regenerating inflationary scenario for an open Universe entails one-field or two-field models of chaotic inflation (see, *e.g.,* Hawking and Turok [132] or Barvinsky [133] and the review by Garcia–Bellido [134]). However, all of these models have run into difficulties which are currently being addressed. Of course, the theory of reheating of the Universe after inflation is a vitally important application of the quantum theory of particle creation, as almost all the material of the Universe was created during this process. A detailed discussion is offered by Linde [112] among others, and it is anticipated that a consistent and satisfactory account will be rendered in the foreseeable future. The text by Liddle and Lyth [135] provides an excellent recent presentation of cosmological inflation and large-scale structure of the Universe in the form of a critical examination of its evolution. Another epoch that is currently much under study is the period of reionization. The finding of a Gunn-Peterson trough caused by neutral hydrogen in the intergalactic medium in the spectrum of the $z = 6.28$ quasar by Becker *et al.* [32] suggests that the mean ionizing background along the line of sight to this quasar (as compared with that for somewhat lower-z quasars) has declined significantly from $z \sim 5$ to 6, and the Universe approaches the reionization epoch at $z{\sim}6$. Doroshkevich and Dubrovich [136] have recently discussed observational tests for the period of reionization and in particular consider negative intensity patches in angular variations of the CMB to be an important probe thereof. The main accomplishment, nonetheless, remains the confirmation of a *flat* Universe and thereby the density-parameter condition that $\Omega_m + \Omega_\Lambda = 1$.

5.2. Accelerated expansion of the Universe

Of equal significance to cosmology is the clear indication that after a prolonged period of decelerated expansion [49] to around one-half of its present age, the Universe entered, some 5 Gyr ago, upon a phase of *accelerated* expansion [21, 45] as the cosmological constant Λ (or "dark energy" or its scalar field, "quintessence") took hold and dominated over matter energy. The credit for establishing this radical revision in cosmological precepts rests with two principal competing groups investigating SNae Ia, namely the High-z Supernova Search Team of Riess *et al.* [18] and the Supernova Cosmology Project of Perlmutter *et al.* [20]. Both groups had found and measured the near infra-red spectra of several dozen supernovae out to moderately high redshift-distance ($z \sim 0.3$–0.9), finding clear indications that the farthest SNae were fainter than would correspond to decelerating, or even coasting, cosmic expansion (the apparent magnitudes of SNae beyond $z \sim$

0.6, plotted *versus* the redshift in a Hubble diagram lay distinctly higher than would correspond to decelerating or coasting expansion). The issue was clinched by the discovery [19] of the farthest known supernova of type Ia, SN 1997ff at $z = 1.7 \pm 0.1$, which had serendipitously been recorded in fine detail by the HST infrared camera, NICMOS at the same time as the brief outburst had been monitored by the HST Wide-Field Planetary Camera, WFPC-2. This confirmed that the surprising faintness of SNae in the $z \sim 0.4$–0.9 region could not have been due to some peculiar intergalactic grey dust or simple luminosity evolution (or low metallicity in early epochs of star formation), but had to be interpreted as the accelerated flight of a "standard candle" that had been ignited in the earliest epoch of star formation. After some 5–8 Gyr of *decelerated* expansion, the Hubble flow changed to *accelerated* expansion as the "dark energy" represented by the cosmological "constant" outweighed the matter energy. The notion of a time-dependent Λ had been advanced prior to these findings (see, *e.g.,* the review by Overduin and Cooperstock [137] and references therein); a recent paper by Novello, Barcelos-Neto and Salim [138], following these developments, now puts forward an explicit model for a spacetime-dependent Λ that offers a mechanism for possible quantum behaviour at the early stages of the Universe.

The question of whether measurements of luminosity distance to SNae Ia from high-precision missions such as SNAP [139] can probe the equation of state of "dark energy" has been posed by Astier [140], who noted that if dark energy is modelled by a scalar field, its equation of state will in general vary with time and be related to the potential of the field. Concluding that with a sufficiently accurate value of the matter density Ω_m (which, in principle, might be derived from large-scale weak lensing in the SNAP satellite mission itself) as a prior, conservative estimates for high statistics in the data would offer good prospects for the determination of the dark energy equation of state and excellent diagnostic criteria. Along similar lines, Weller and Albrecht [141] have examined the feasibility of using such enhanced data sets to discriminate among different dark-energy theories (including, for instance, the supergravity SUGRA model) with a view to deriving universally acceptable hypotheses for the nature of dark energy, dark matter and supergravity. This will be explored further in the next subsection.

5.3. Dark secrets: dark energy and dark matter

Dark energy differs from matter in being intrinsically relativistic, homogeneous and all-pervasive (rather than clumping like matter). In its equation of state relating its pressure p to its density ρ via the relation $p = w\rho$, the constant of proportionality w has different characteristics according to the physical model used in the description of such dark energy as the "driver" of accelerated expansion: *e.g.*, $w = -1$ for vacuum energy (as expressed by the cosmological constant Λ); w lies between -1 and $+1$ (and is time-varying) for a rolling scalar field, while $w = -N/3$ for a network of (string-like) frustrated topological defects of dimension N in multidimensional spacetime. Thus, the determination of w (and testing its time-variability) constitutes a primary goal of current cosmological enquiry. Vishwakarma [142] has examined various dark-energy models in the light of the SN 1997ff outburst, rejecting some as incommensurate with the data while retaining the above-mentioned alternatives. At $z \sim 1.7$, the SN 1997ff supernova event occurred in the early Universe before the era of Λ-dominance while the expansion of the cosmos was still slowing down due to gravity. Because of its remoteness, SN 1997ff currently represents the best object for investigation of this tortuous (and torturous!) subject. In a brief critical study of the topic, Turner [44] also concluded that distant SNae offer the best possibilities for resolution of this question, while admitting the likelihood that new physics might well be engendered by its pursuit. Indeed, in a later synopsis [143] he summarized the current situation admirably: "A successor to the standard hot big-bang cosmology is emerging. It greatly extends the highly successful hot big-bang model. A key element of the New Standard Cosmology is dark energy, the causative agent for accelerated expansion. Dark energy is just possibly the most important problem in all of physics. The only laboratory up to the task of studying dark energy is the Universe itself."

Hand in hand with the task of establishing the nature of dark energy is the problem of DM, which, of course, has appreciable *attractive* gravitational mass. A recent symposium [16] was devoted to this topic and a torrent of publications continues to issue with the aim of elucidating the discrepancy between observed (luminous) matter and invisible gravitating matter. This long-standing problem was first raised by Zwicky in 1933: in large spiral galaxies the rotation rate of ionized atomic hydrogen clouds (H II regions) remains constant radially (likewise that of satellite galaxies out to large distances from the galactic centres), implying that the enclosed mass increases with radius well beyond the distance at which no more stars are seen. This observation also holds for elliptical galaxies and is particularly cogent for dwarf galaxies, which are totally dominated by dark matter, or for clusters of galaxies, in which the rotation curves again flatten out with radial distance, without evidence of dispersion. The baryon density (listed in Table I) clearly indicates that a fractional component of the dark matter has to be baryonic [144, 145]. Yet that alone is altogether insufficient to account for the dark matter at large scales (the baryonic density inferred from nucleosynthesis is far too small by roughly a factor of 6), as the COBE, etc. data reveal. It may even be that a claim [146] of a first sighting of a new kind of "cold" white dwarf in the MW galactic halo might persuasively account for objects able to provide for up to one-third of the dark matter in the Universe (albeit hotly disputed, as past claims, *e.g.,* by groups such as the MACHO Collaboration, were subsequently disproved). The low surface temperature (< 4500 K) of the newly-discovered "cold" white-dwarf species is deemed to induce interacting hydrogen molecules in the stellar atmosphere to temporarily take on molecular moments in the aftermath of intermolecular collisions, thereby causing them to absorb light more strongly at most optical wavelengths and thus appear ultra-faint. At one extreme, candidates for dark matter include Massive Compact Halo Objects (MACHOs) while at the other extreme are Weakly Interacting Massive Particles (WIMPs), possibly "Hot" Dark Matter (HDM) neutrinos, which once were in thermal equilibrium and have such slight mass that they move ultra-relativistically, or heavy neutrinos (right-handed electron neutrinos have recently been suggested as long-lived, superheavy dark matter [147]), or, more likely, the neutralinos postulated in SUperSYmmetric (SUSY) theory which, although they too were once in thermal equilibrium, have sufficient mass to have caused them to slow down in the meantime to low velocities and thereby constitute *cold* dark matter. Also currently in favour are other exotic CDM particles, such as axions (extremely light, but never in thermal equilibrium, having been formed in very cold conditions), or possibly free-floating clumped matter of planetary mass. Tentative evidence for the latter in one of the MW galaxy's halo globular clusters has recently been adduced by Sahu *et al.* [148] from gravitational microlensing studies. A method of probing galaxy halos for DM substructure in the form of clumps of material surrounding remote quasars using compound gravitational lensing, in which only a small fraction of the lens surface density is contained within the subhalos, has been proposed by Metcalf and Madau [149]. This has to be distinguished from conventional gravitational lensing, as caused by stars in the lens galaxy, since in compound lensing the density is not isotropic. A signature of the compound-type lensing is the characteristic distortion of the lensed images on milli-arcsecond scales due to the topography of the substructure in the lens.

So far, no convincing evidence has been adduced either for MACHOs (despite searches since 1992 by at least four principal groups: the Anglo-American MACHO collaboration, the DUO and EROS teams, and the European OGLE project) or for WIMPs (*e.g.,* by the EDELWEISS collaboration [150]). Moreover, very low-mass (mini-)black holes (BHs) cannot form the bulk of dark matter, as they would evaporate through Hawking radiation and yield characteristic high-energy gamma-ray emission. It has also been demonstrated [151] from a combination of EROS and MACHO microlensing results in the direction of the LMC that the mass region from 10^{-7} to 10^{-1} solar masses is excluded from the set of candidates for DM in the galaxy halo. This includes mini-BHs and brown dwarfs. It is true that, by this criterion, primordial BHs of a solar mass or more could behave as Cold Dark Matter (CDM), but the likelihood is very slight.

Notwithstanding, gravitationally-attractive CDM of *some* kind remains the current favourite in a model that also admixes (repulsive) dark energy in a composite ΛCDM model. Whatever be the actual nature of the CDM, the particles cannot move far enough to damp perturbations on small scales; hence structure arises by "coagulation from the bottom up" beginning at redshifts $z \sim 2$–4 with the formation of galaxies and their subsequent assembly into galactic clusters and super-clusters.

Of the present, very fluid, situation one can say only that the stage has been set and the ΛCDM model in its various guises, having performed its definitive Cold, Dark, Mysterious role in the universal drama of cosmology while under intense critical scrutiny, is now at last moving centre-stage into the spotlight of identification and recognition to receive its due acclaim.

6. Nuclear astrophysics

There can be no doubt that, at least in part but not in its entirety, dark matter includes baryonic (CDM) and neutrinoic (HDM) components. If the bulk of the DM consists of relic particles, such as neutralinos, axions or neutrinos, all of which by their very nature have extremely weak interaction with matter and thus are immensely hard to detect, they should be evident in our MW galactic halo and have a local mass density on the order of 10^{-21} kg m^{-3}. Searches for neutralinos of mass 10–500 GeV or halo axions of mass 10^{-6}–10^{-5} eV are currently underway, without convincing results as yet.

6.1. The role of neutrinos in cosmology

As for neutrinos, the Sudbury Neutrino Observatory (SNO) group [25] and the SuperKamiokande (S-K) collaboration [26] have now unambiguously established that quantum oscillations [152] occasion mixing of neutrino flavours (between electron, ν_e, muon, ν_μ, and taon, ν_τ, species). This enabled mass to be assigned (very approximately) to each of these varieties: $m(\nu_e) \sim 3 \times 10^{-5}$ eV, $m(\nu_\mu) \sim 3 \times 10^{-3}$ eV, and $m(\nu_\tau) \sim 10^{-1}$ eV. A framework for unification of the three neutrino species has been proposed by Chankowski, Ioannisian, Pokorski and Valle [153], suggesting that the neutrino masses and mixings observed at low energies combine into a very simple form at some high mass-energy scale. Such "unification" mass cannot be the Planck mass, as the neutrino masses would be too small to account for the atmospheric neutrino anomaly, but would most likely lie in the eV range, with neutrino mass splittings induced by renormalization effects associated with SUSY thresholds.

Interestingly, a four-neutrino scheme has been put forward by Caldwell and Mohapatra [154] and Peltoniemi and Valle [155] invoking a *sterile* neutrino, ν_s, as the fourth member. In this, $\nu_e \to \nu_s$ decay was postulated to account for the solar ν_e deficit, while the ν_μ and ν_τ remaining heavier members of the ν family served as constituents of hot dark matter. Expanding upon this, Caldwell, Mohapatra and Yellin [156] have shown that remanent difficulties with the three-neutrino scheme can be removed under the aegis of superstring (brane) theory involving a large extra dimension to accommodate 5-dimensional Kaluza-Klein oscillation modes. The solar experiments suggest a dimensional size of $\sim 6 \times 10^{-5}$ m for this, the effect of which should be discernible by dips in the SNO spectrum and by gravity experiments. However, Berezinsky [157] has carried out a further analysis of the combined SNO and S-K data, concluding that oscillation to sterile neutrinos is excluded at the 3.54 σ level (while at this level of confidence, oscillation to *active* neutrinos is confirmed, albeit with some reservations).

In addition to these attempts toward resolving the "solar neutrino problem" and associated difficulties, the models have clear relevance to cosmology. Thus, Mbonye [158] has explored the dynamics of neutrinos in a vacuum-dominated cosmology, finding that a phase would be induced in the propagation of a massive neutrino, and that delay would ensue in their flight-times compared to those in null fields. With the presently observed background vacuum energy density both effects become non-trivial for neutrino sources further away than ~ 1.5 Gpc, offering the means for independent constraints on the dark energy density and the deceleration parameter to be established.

Furthermore, Kirilova and Chizhov [159] have recently reviewed cosmological nucleosynthesis under inclusion of neutrino oscillations. In their survey, they identified specific effects and examined the importance of these in the primordial production of ^{4}He (they also updated the quantitative cosmological constraints on active/sterile neutrino oscillation parameters).

6.2. Nuclear astrophysics

Primordial nucleosynthesis-yields play a central role in cosmology as they pertain to the evolution of the Universe. Of relevance to the previous subsection is the determination of the primordial ^{4}He production relative to hydrogen, $Y_{\rm P}$, since when the baryon density Ω_b is known (*cf.* Table I and below), the number of light-neutrino species is pinned down [160] to being 3 (actually, if $Y_{\rm P} < 0.25$, then $N_\nu < 3.4$ on the basis of baryon density inferred from measurements [161] of the primordial deuterium abundance).

Some of the current quests in nuclear astrophysics have been described and discussed in the comprehensive review by Käppeler, Thielemann and Wiescher [162], as well as at the present School. Big-Bang Nucleosynthesis (BBN) during the first 3 minutes of the Universe entailed a sequence of nuclear reactions that produced the light elements ^{2}D, ^{3,4}He and ^{7}Li; their abundance pattern as a function of the baryon density ρ_b constitutes a sensitive test of the Standard Model. In particular, the abundance of ^{2}D is very sensitive to the density of baryons, and measurements [161, 47] of the deuterium abundance in clouds of hydrogen at high redshift have pinned down the baryon density to 10% precision as $\Omega_b = (0.020 \pm 0.002)h^{-2}$. Moreover, O'Meara *et al.* [163] have measured the D/H abundance ratio in absorption-line systems toward QSO's and thence found the baryon density to be $\Omega_b = (0.0205 \pm 0.0018)h^{-2}$, while the baryon-to-photon ratio was determined as $\eta = (5.6 \pm 0.5)\times 10^{-10}$.

One of the long-standing puzzles, posed by Sakharov [164], that has not yet been satisfactorily resolved is the baryon asymmetry of the Universe: why are there practically no antibaryons? The asymmetry implies that in the early Universe there existed only one extra quark per approximately one billion quark-antiquark pairs. Sakharov propounded three conditions that have to be satisfied at a certain early stage of evolution for this to arise: *(i)* baryon number, B, must not be conserved; *(ii)* thermodynamic equilibrium must not exist, and *(iii)* CP-symmetry must be broken. In principle, these could be fulfilled by the Standard Model [165], inasmuch as *(i)* a nonperturbative mechanism exists for B-violation; *(ii)* thermodynamic equilibrium may be strongly violated if the electroweak phase transition is of 1st order; *(iii)* the CP-violating phase in the Cabbibo–Kobayashi–Maskawa matrix allows for CP-violation [2]. However, the requirement of a *small*-mass Higgs boson ($m_{\rm H} < 50$ GeV) for the necessary conditions to be satisfied has meanwhile been ruled out by the finding at LEP-II that $m_{\rm H} > 95$ GeV. It still remains possible [2] within the Minimal Supersymmetric Standard Model (MSSM) framework [166] that if the mass of one of the partners of the t-quark, namely the right t-squark, be reasonably small, $m_{tS} < 175$ GeV, and the mass of the lightest Higgs boson also be limited to $m_{l\rm H} < 115$ GeV, then the Sakharov criteria may apply. This, or any other more complicated extension of the Standard Model designed to provide electroweak generation of the baryon asymmetry, remains to be tested in future investigations.

With this brief overview of some aspects of nuclear astrophysics relevant to cosmology, it is necessary, within space limitations, to pass on to considerations of some of the more speculative ventures in this domain, such as string and superstring developments.

6.3. SUSY, supergravity, cosmic strings and the New Physics

As Kane [167] has indicated, by last year more than 10,000 papers on supersymmetry had been published, and by now this number has well-nigh doubled as the New Physics has taken hold. This includes GUTs, unification, Higgs and MSSM physics (with such super-partners as neutralinos, sneutrinos, axions, gravitinos, winos, zinos, *etc.*), the hierarchy problem, proton decay, and so on. Kane has edited a fairly comprehensive up-to-date overview [168] which surveys the salient features of SUSY. The Proceedings [169] of an international conference in 2000 celebrating 30 years of the development of SUSY also provide an excellent perspective and many relevant details. Exciting new developments are anticipated in this field as experiments with high-energy accelerators and theoretical advances shed fresh light upon current views of the Universe, from the minuteness of the Planck scale to the immensity of its outermost reaches.

As for string and superstring theory (or, more generally, M-brane theory), a brief survey of the structure of cosmic strings has recently been presented by Peter [170]. As he points out, topological defects in general, and cosmic strings in particular, are among the most important predictions of Grand Unified Theories (GUTs). They may well be partly responsible for the fluctuations of the CMB [171] and for the formation of large-scale structures in the cosmos, as also for other cosmological phenomena. Even more challenging is the conceivable prospect of cosmic strings carrying a current, as vortices ("vortons") can then be formed, which under suitable conditions might be responsible for certain high-energy cosmic rays. In this connection, the nature and detection of ultra-high energy cosmic radiation has been surveyed in an Essay Review by Sheldon [172], including the suggestion of "strangelets" (baryon-like agglomerates of Strange Quark Matter made up of an equal number of up (u-), down (d-), and strange (s-) quarks as a MACHO constituent of CDM, proposed by Edward Witten in 1984 and reviewed in this School by Rybczynski, Wlodarczyk and Wilk.

Quantum string cosmology has also been considered by Dabrowski [173], including an examination of super-inflation scenarios in the early Universe. Hogan [174] has addressed the question of "why the Universe is just so" within the context of GUTs and the anthropic principle. The fine tuning required by the presently-observed circumstances remains an intriguing challenge for elucidation.

In a different vein, Tye and Wasserman [175] have investigated a 3-brane-world solution in 5-dimensional spacetime to the cosmological constant problem ("Λ numerically many orders of magnitude smaller than expected within the context of ordinary gravity and quantum field theory"). In their model, Λ becomes exponentially small (compared to other scales) for two parallel 3-branes separated by an (expanding) distance L. In an extension of these ideas, they even raise the notion of a multibrane scenario in which the separation distances between branes play the roles of various scalar fields (*e.g.,* the separation between two nearby branes may play the role of an inflaton [176, 177] while the separation between two far-apart branes may assume the role of a quintessence field [178]).

A report by Albrecht, Burgess, Ravndal and Skordis [179] examines the cosmological implications of brane-world scenarios having large ($\sim$ mm!) extra dimensions. In such super-dimensioned models, moduli like the "radion" appear to be extremely light, with a mass of order 10^{-33} eV, allowing them to play the role of the light scalar of quintessence models. The report considers favourable and unfavourable aspects of such models that pertain to the eras following nucleosynthesis and describe the features that have to be satisfied in pre-nucleosynthesis epochs of cosmology.

Brax and Davis [180] have anayzed brane-world singularities, emphasizing the case of $N{=}2$ supergravity in singular spaces, unbroken and viable in the bulk but broken in the brane-world. The breaking of SUSY produces a brane-world metric of the Friedmann–Robertson–Walker type with an acceleration parameter $q_0 = -4/7$ and an equation-of-state proportionality factor $w = -5/7$. It again turns out here too that exquisitely-fine tuning is required in the amount of SUSY breaking, but a study of the naked singularities inherent in self-tuned branes or the supergravity in singular spaces renders the model reasonable and leads to a natural cosmological evolution of the Universe with a late stage of acceleration and a cosmological constant consistent with the latest experimental findings.

These rushed and all-too-cursory glimpses of current activity in a thriving field of research can provide only a smattering of the developments at the forefront of scientific investigation in our day. This beautiful Universe of ours provides enormous scope for imaginative, intellectual, intensive enquiry; there is still so much that remains to be elucidated and, best of all, so very much to provoke and stimulate our sense of awe and wonder.

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Note added in proof:
The American–Australian MACHO Project group have just announced [181] the first reliable microlensing evidence for a possible MACHO in our galaxy of a very faint red dwarf star in the Large Magellanic Cloud (LMC) in a Published Letter entitled *Direct Detection of a Microlens in the Milky Way*. This observation was gleaned from an 8-year study of more than ten million stars in the LMC galaxy, monitoring their brightness, time-variability and spectra, to amass data from a combination of VLT studies at the Mount Stromlo Observatory in Australia and the Hubble Space Telescope. The survey results so far indicate that between 8 and 50 percent of the baryonic mass of our Galactic halo is in the form of MACHOs. Insofar as baryonic MACHOs of planetary mass are concerned, it bears noting that to date some 80 extrasolar planets have been detected by Doppler-shift studies of the wobble of their parent stars, since the finding in 1995 by Mayor and Queloz [182] of such a body circling 51 Peg with a 4.23-day period at a radius of 0.051 a.u. (astronomic units) [183]. Of these 80, at least one circles a star (47 Ursae Majoris) in our own Milky Way galaxy at a radius of 2.1 a.u. and with a period of 1098 days [184] (indeed, it may be supplemented by a second orbiting planet with a period of 2594 days at a radius of 3.73 a.u.). Another instance of a multiplanet system is that around Upsilon Andromedae, which has 3 confirmed planets orbiting with 4.6170, 241.2 and 1266.6 days, respectively, with semiminor axis values of 0.059, 0.83 and 2.50 a.u. Another very interesting recent finding [185] has been that of an extrasolar planet that has an atmosphere containing sodium (among other elements still being analyzed); it orbits the star HD 209458 with a period of 3.5 days. In addition to the above, there are at least two confirmed planetary systems orbiting pulsars (*viz.* PSR 1257 + 12 and PSR B1620–26) and at least one extrasolar multiplanet system. For the latest information on extrasolar planets, an excellent source is The Extrasolar Planets Encyclopaedia maintained by Schneider [186]. More findings are expected to follow.

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