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INTRODUCTION

(R. B. Partridge)

As the following reports show, there has been a great deal of activity in cosmology in the past three years, particularly, I would say, on the observational side. For instance, measures of Hubble's constant H_o, both physical and geometrical, are pouring in (see Trimble's contribution below), and we should soon realize the promise of the Hubble Space Telescope in refining values of H_o. Interest in a non-zero cosmological constant Λ has resurfaced, driven in part by new observational results.

The gravitational lensing of distant sources has provided new means to probe both the properties of high redshift objects and the distribution of mass (both luminous and "dark" matter) in the lensing objects. As Fort suggests in his article below, observations of lensed sources may povide a value of H_o as well. A useful summary is provided by the volume *Gravitational Lensing* edited by Mellier *et al.* (Springer–Verlag, 1990).

A major recent trend in cosmology is the deepening and refining of surveys of extragalactic objects. I refer to both counts (see Colless below) and redshift surveys of galaxies, IRAS sources, QSO, etc. A great deal has been learned about the evolution and large-scale structure of the Universe from these systematic surveys (see Dekel's paper in our report of 3 years ago). This survey work is one mark of the maturing of our field.

Another, I would suggest, is the increasing interconnection between cosmology and microphysics. Limits on the number of neutrino families derived from nucleosynthesis calculations and the observations of primordial 4He have now been confirmed by accelerator experiments (see Denegri *et al.* , *Rev. Mod. Phys.* **62**, 1, 1990). The need for "dark" matter, probably non–baryonic, has been established by a number of astronomical observations (see *IAU Symposium 117*) and laboratory searches are now underway for possible candidate particles (see Sadoulet below).

Important information on the origin and evolution of large–scale structure in the Universe was provided by the U. S. COBE satellite (see G. Smoot *et al.* , *Ap. J. (Letters)*, **396**, L1, 1992). An instrument on that satellite detected, at a level of one part in 100,000, the fluctuations in the cosmic microwave background that astronomers had been searching for for more than two decades. The observations and their interpretation are summarized below. The Proceedings of the "Texas Symposium" held in Berkeley, California in Dec. 1992 will also be useful.

I will close by noting the role of advanced technology–large–aperture telescopes, CCD detectors, advanced cryogenic particle detectors and space platforms–in many of these advances in cosmology.

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Cosmological Parameters

(V. Trimble)

The fundamental parameters are H (expansion rate), Ω (density in units of the critical density), and Λ (cosmological constant). Derivable from these are q_o (deceleration, k (dimensionless radius of curvature), and to (present age). The fraction of the critical density in baryons, Ω_b, is generally also regarded as important. The standard model thus defined is alive and well[1]. The triennium has seen a number of limits on fifth forces, distance dependence of G, alternatives to general relativity, and tired light effects[2], but no new positive results. Polarization of the community on large vs. small values of H has persisted; some progress has been made in constraining L from statistics of gravitationally lensed QSOs (see following paper); and it has become increasingly clear that none of the tricks yet thought of can reconcile Ω_b=1 with the apparent primordial abundances of H^2, He^3, He^4, and Li^7.

The traditional angular diameter test, interpreted as a constraint on q_o, favors $q \simeq 1/2$ from radio data[3] and nearly rules it out from optical data[4]. But disentangling evolutionary effects from cosmological effects remains sufficiently difficult as to cast doubts on all results[5]. Other geometrical tests present other problems, and must be properly corrected for effects of gravitational lensing, interstellar scintillation, and internal absorption in galaxies[6].

The most direct measurements of Ω come from analyzing the peculiar velocities of galaxies in clusters or on larger scales. Reported values range[7] from 0.03 to 1.0, with many equally carefully calculated ones in between[8]. Disagreement persists both on whether the necessary data actually exist and on whether the calculations have been done correctly[9]. We can say with some confidence that the universe is not closed by gravitational radiation (at some wavelengths), by black holes (of some masses) or by 17 keV neutrinos, though the tau neutrino remains intriguingly close to the necessary mass on some hypotheses[10] (see paper by Sadoulet here). Not surprisingly, less direct methods (incidence of cluster substructure, merger rates) also yield values from about 0.1 to 1.0.

Globular clusters remain a better constraint on to than either local stellar populations or the nucleocosmochronometers, because the halo came first and the disk apparently formed inside out[11]. There is a real spread in cluster ages[12], but only the oldest matter for our purpose. Standard physics and a solar mix of metals lead to cluster ages up to 16-19 Gyr[13]. Popular ways of decreasing this are non-solar mixes (high 0/Fe or alpha nuclei), inward diffusion of helium, and unexpectedly efficient convection[14]. Each allows a decrease of at most 1-3 Gyr (groups do not entirely agree). The modified ages remain impossible if both H and q_o are large. Moving the galactic center away is a less popular but possible solution[15]. A similar, though less sharp, conflict arises in interpreting the evolving colors of galaxies unless the universe is rather old[16].

The universe is not closed with baryons. The triennium began with some enthusiasm for $\Omega_b = 1$ and inhomogeneous nucleosynthesis, but this has gradually faded[17], and other ways of pushing on the standard model have not met with much success[18]. D/H and Li^7 both put limits on Ω_b,[19] which must fall between 0.01 and 0.09 for any reasonable choice[20] of H. The primordial abundance of He is currently the most worrisome quantity. No set of standard model parameters can accommodate Y_p below 0.237. This is within the error bars of most, but not all, recent determinations[21]. The standard model abundances are a viable starting point for galactic chemical evolution[22], and may permit everything in the universe to have the baryon/total mass ratio of typical rich clusters but not that of Hickson compact groups[23]. Among remaining alternative models, non-zero lepton number is perhaps most worthy of further exploration[24].

To reconcile globular cluster ages with $k = 0$ and $H \geq 60$ km/sec per Mpc requires a cosmological constant in the (dimensionless) range 0.74-1.0[25]. So large a value puts lots of volume at large redshifts, and so predicts large numbers of gravitational lenses and a rapid increase in numbers with z[26]. In fact lensing seems to be quite rare and the distribution with z rather flat, implying[27] $\lambda \leq 0.9$, though evolutionary effects still need to be taken into account[28]. Nevertheless, the cosmological constant is sufficiently back in favor to make recent calculations of look back time, luminosity distance, etc. in such universes a useful contribution[29].

The value of the Hubble constant is not (as Sandage wrote a generation ago) presently well known. At least 39 values were published in the triennium, based on nearly as many calibrators. The list, in order of publication (or at least arrival on the library shelves), with the references in the same order[30] is: 81-94 (PNe in Virgo), 46 ± 10 (SN Ia's), 78 or 64 (surface brightness fluctuations in Virgo galaxies), 70 ± 7 (Virial mass = stars + gas in Mich 160), 52 (Virgocentric infall = 168 km/s), 75-100 (SN Ia's calibrated in Virgo),

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50 ± 11 (time delay in lensed QSO), 75-95 ± 20 (lensed arcs), 70 (luminosity function of globular clusters in Virgo E's vs. MW), 55 (decaying neutrinos as dark matter), 82 ± 7 (surface brightness fluctuations in Fornax and Eridanus), 42-69 (time delay in lensed QSO 0957, radio data), 85 (brightest stars in Virgo), 100 (PNe and surface brightness fluctuations), 92 ± 20 (Tully-Fisher in Coma), 63.5 (QSO 0957 angular diameter distance), 40 ± 9 (Sunyaev-Zel'dovich effect in A665), 80 (Cepheids), 90 ± 17 (Tully-Fisher), 60-80 (SN Ia model), 85 (PNe and Cepheids), 86 ± 14 (SN 1937C in IC 4182, calibrated on red supergiants), 61 ± 10 (SN Ia model), 65 ± 10 (SN 1972C in NGC 5253 calibrated on HII's), 80 ± 15 (Tully-Fisher), 85 (red and blue supergiants in Virgo), 60 ± 10 (SN II photosphere models), 80 ± 7 (many), 76 ± 9 (Virgo-Coma distance moduli), 44-63 (shape of galaxy luminosity function), 51-77 (brightest cluster galaxies), 45 ± 9 (SN 1937C in IC 4182 calibrated on Cepheids), 43 ± 11 (ScI angular diameters), 53 ± 10 (surface brightnesses of MW and Virgo), 45 ± 12 (angular diameters vs. M31), 10 (large scale streaming), 32, 68, or 87 (lensing of 0957), 61-66 (Tully-Fisher with halos removed), 54-64 (SN Ia model light curves). The unweighted median is 67 km/s per Mpc, and I am willing to be that this is within 35 km/s per Mpc of the truth. One thoughtful reviewer[31] has reached a similar conclusion.

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Gravitational Lenses
(Bernard Fort)

With the improvement of astronomical instrumentation, Gravitational Lensing (GL) has become a remarkable technique for observational cosmology. The number of publications in major journals is $\sim 10^2$ per year, so that here we can only report a small, representative sample to highlight some major issues.

The cosmological applications of GL were recently reviewed (Blandford and Narayan 1992), and the state of the theory and observations prior to 1991-2 is thoroughly presented in the first monograph on the subject (Schneider *et al.* 1992). In addition, there are the proceedings of biannual meetings on Gravitational Lenses (e.g. Surdej *et al.* 1994, Kayser *et al.* 1992).

To start from multiple quasars, there have been new subarcsecond seeing surveys with the HST and with ground based radio and optical telescopes. Several new candidates have been discovered : 1208+1011 (Bahcall *et al.* 1992a, Magain *et al.* 1992), HE 1104-1805 (Wisotzki *et al.* 1993), B1422+231 (Patnaik *et al.* 1993), and BRI0952-01, which is the most distant gravitationally lensed QSO with a redshift z = 4.5 (MacMahon *et al.* 1992).

GL statistics constrain the density parameter $\Omega_{10:12} < 0.02$ for intergalactic compact objects of mass $M_{ico} \sim 10^{10} - 10^{12} M_\odot$ (Surdej *et al.* 1993 and references therein), and $\Omega_{7:9} < 0.4$ for $M_{ico} \sim 10^7 - 10^9 M_\odot$ (Kassiola, Kovner and Blandford 1991); and QSO variability provides constraint $\Omega_{-3:-1.5} < 0.1$ for intergalactic compact objects of mass $M_{ico} \sim 10^{-3} - 10^{-1.5} M_\odot$ (Schneider 1993). The evidence against a large, $(\Lambda/(3H_o^2) \sim 0.9)$ cosmological constant (Fukuhgita *et al.* 1992 and references therein) has also been confirmed by HST observations (Maoz et *al.* 1993), and by statistical analysis of uncertainties (Kochanek 1993, ApJ, in press). Lensing of extended radio-sources can be a better cosmographical probe than the lensing of unresolved sources (Kochanek 1993). Clear statistical evidence that galactic cores are fairly small has been presented (Wallington and Narayan 1993, Kassiola and Kovner 1993).

There was further progress in investigations of individual interesting multiple QSO cases: — Radio observations of MG0414+0534 confirmed that one of the (formerly) three components was a close pair separated by 0.5", as it should be for a simple lens (Katz and Hewitt 1993); and optical deep imaging revealed the lensing galaxy (Schechter et Moore 1993). New VLA data (Patnaik *et al.* 1993) has been published on B0218+35.7 which is favorite candidate for the determination of H_o, due to its two compact and strongly variable components, its radio ring, and the smallest separation known, $0''.335$. Observations of UM673 provided a measure of the size of the intervening Lyman alpha clouds (Smette et *al.* 1992).

The K-band observations are particularly promising because the seeing is better, and high redshift galaxies can be more luminous. In particular, they made it possible to detect the deflecting galaxies in Q2016+112 (Heflin *et al.* 1991, Lawrence *et al.* 1993). There was also the important effort to extend the observations to near infrared in other cases, e.g Q2237+030 (Nadeau *et al.* 1991), PG1115 +080, H1413+117, and Q1429-008 (Hewitt et *al.* 1992, Annis and Luppino 1993), the radio ring MG1131+0456 (Annis 1992), and B1422+231 (Lawrence *et al.* 1993). It will also be necessary to perform IR spectroscopy of multiple QSOs which can have unusual R-IR spectrum like MG0414+0454 (Hewitt *et al.* 1992).

Two new radio rings , 0218+357 (O'Dea *et al.* 1992) and MG 1549+3047 (Lehar *et al.* 1993), raise their total number to 5. Rings provide a unique opportunity to model the mass distribution in the foreground galaxy and to reconstruct the extended source with an algorithm inverting the lens (Kochanek and Narayan 1992). It may be possible to observe $\sim 10^2\ deg^{-2}$ similar optical rings with the HST resolution (Miralda-Escude and Lehar 1992)

The first attempts (Kronberg *et al.* 1991) have been made to constrain mass distributions of galaxies using the facts that the change of polarisation of light by realistic GL is extremely small (Dyer and Shaver 1992), and that there is a tight coupling between the intrinsic polarization angle and the orientation in radio jets.

The procedure for determination of H_o requires direct measurement of the velocity dispersion of the lens galaxy. Such measurements have been undertaken for Q2237+0305 (Foltz *et al.* 1992) and Q0957+561 (Rhee 1991). The first discovered GL, Q0957+561, remains an attractive case for observing and modelling. The value of H_o obtained from modelling Q0957+561 is disturbingly low (Falco *et al.* 1991a), although an analyses of systematic errors (Kochanek 1991) relaxes this problem to $0 < H_o < 90 \pm 30$ (for other values of H_o see the paper by Trimble here). This lens appears to be quite complex, with the discovery of a large fold arc nearby (Berstein *et al.* 1993) and of a background group of galaxies at $z = 0.503$, in front of the QSO (Garret *et al.* 1992, Soucail and Angonin 1993). Incidentally, the magnification of the lens makes it possible to detect intrinsic X-ray emission of Q0957+561 (Jones *et al.* 1993). The effect of microlensing on estimates of the time delay has been investigated (Falco *et al.* 1991b). There is still a controversy on the value of the time delay, although the majority vote for $T = 1.45 \pm 0.04$ years (Press *et al.* 1992a,1992b, Oknyanskij and Beskin 1993, and references therein). If so, there is an interesting evidence that the compact radio source lags by 6.6 years behind the optical one, and that its size of the central radio source is not larger than that of the optical source, so that it can also be microlensed (Oknianskij and Beskin 1993).

The reported excess of foreground galaxies near highly luminous QSOs is still a matter of debate (Schneider 1992, Romani and Maoz 1992). However, there is a new interesting development: in 1990 Fugmann found correlation between galaxies from the Lick catalogue and $1Jy$ distant radio sources. Bartelman and Schneider (1992) studied this correlation further and found that it persists on an angular scale of 6 arcmin. They also found (Bartelmann and Schneider 1993a,b) that gravitational lensing by large scale structures can account for such correlations. An important factor in these correlations is the double magnification bias (Borgeest *et al.* 1991) which applies when the quasar sample has a double threshold, radio and optical, and the radio and optical fluxes are not correlated. Obviously the effect of smooth large-scale structure is too small, but superimposed granular distributions on the scale of clusters may significantly enhance the overall effect (Babul and Lee 1991, Jaroszinki 1991,1992).

Microlensing studies are becoming spectacular with large programmes of QSO monitoring (Surdej 1994) because it is a unique way to see whether there is some dark matter in the form of compact objects, ranging from massive black holes to brown dwarfs. The influences of source size (Refsdal and Stabel 1991), external shear (Mao 1992a), and transverse motion (Kayser 1990, Grieger *et al.* 1991, Wambsganss 1992, Witt 1993) have been theoretically investigated. It appears that for typical halos of galaxies, single microlens events are unlikely and result in a very complex pattern of moving caustics (Rauch *et al.* 1992). In particular, the effects of random motions of individual stars in a lensing galaxy are not negligible as compared to the effects of the the relative motion of the source, the lens galaxy and us (Kundic and Wambsganss 1993). Microlensing also provides information on the relative sizes of different regions in QSOs (red vs. blue continuum, or emission line regions), which in turn give critical constraints on accretion disk models (Wambsganss and Paczyński 1991a). However, puzzling observations do not allow to clearly disentangle intrinsic variability of QSOs from microlensing events in some cases: GC0248+430 (Borgest *et al.* 1991b), Q0957+561 (Schild and Smith 1991), 2237+03 (Racine 1992), Q2237+03 (Webster *et al.* 1991), AO0235+164 (Saust 1992), and 0414 +0534 (Angonin-Willaime *et al.* 1993).

The original idea of Paczyński (1986) to search for microlensing events from compact objects of the galactic halo in front of the large magellanic clouds (MACHO Searches) has been investigated theoretically (Nemiroff 1991, Gould 1993). Several monitoring programmes are under way in the southern hemisphere (Gould 1992, Griest *et al.* 1991, Vidal-Madjar *et al.* 1993), and similar surveys are suggested towards the galactic bulge (Paczyński 1991) and M31 (Crotts 1991). So far, the null detection within the accumulated period of observations do not permit us to constrain the density of compact objects for any range of masses.

There is also a proposal to search for a gravitational lensing effect of a massive black hole in the centre of our galaxy (Wardle and Yusef-Zadeh 1992). Another interesting proposal (Wambsganss and Paczyński 1992) is to search for possible milliarcsecond patterns in the radio image of multiple QSO, which can be produced by massive black holes in the primary lens galaxy.

In 1986 Paczyński pointed out that gamma-ray bursters at cosmological distances could be a signature of massive compact objects and Black Holes (Mao 1993). Ways to recognize various ranges of lens masses have been considered (Paczyński 1991b, Blaes and Webster 1992, Narayan and Wallington 1992, Gould 1993, Mao 1993, Wambsganss 1993)

Recent lists of large gravitational arcs surveys in rich clusters of galaxies confirm the frequent occurence of arcs in distant X-ray clusters (Surdej Ed. 1994). More than 20 cases are known but deep spectrophotometric data are published for only 12 of them : A370 (Kneib *et al.* 1993), A963 (Ellis *et al.* 1991), A1689 (Tyson *et al.* 1990), A2390 (Pello *et al.* 1991), A2218 (Pello *et al.* 1992), MS0302+1658 (Mathez *et al.* 1992), Cl0024+1654 (Kassiola *et al.* 1992), the cluster-lens MS2137-23 with the first radial arc (Fort *et al.* 1992), MS2053-04, MS1621+26, and MS0440+02 (Luppino *et al.* 1992, 1993), and the most distant cluster-lens Cl2236-04 (Melnick *et al.* 1993).

It is still difficult to learn much about the evolution of clusters and about the properties of the back-

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ground sources from comparing theoretical predictions with the observed statistics (Miralda 1993a,b; Wu and Hammer 1993), since the sample is small and heterogeneous. Nevertheless, the subarcsecond widths of large arcs indicate a steep gradient of the potential which can be understood either in terms of a small core in a pseudo-isothermal distribution or (apparently preferably) of a deVaucouleurs radial profile (Hammer 1991).

This conclusion is in accord with the modelling of the radial arc in cluster MS2137-23 (Mellier *et al.* 1993) which constrained the core radius (30 *kpc*). The second fold arc system showed that the distribution of dark matter follows the ellipticity and orientation of the large faint halo of the bright elliptical galaxy. The bi-polar potential of A370 has been similarly recovered by using newly discovered gravitational pairs (Kneib *et al.* 1993). The cluster Cl0024+1654 must also be dominated by a compact massive halo (Kassiola *et al.* 1993) despite the fact that it does not yet have a cD galaxy at its center. In these three clusters, a comparison of model predictions for extra images with deep photometry and high resolution observations appears to be quite a powerful method to recover the mass distributions. The analytic formulae for GL with elliptic mass distributions (Kassiola and Kovner 1993) arrived just in time for astrometric testing of multiple image predictions.

Besides the gross mass distribution, orientation patterns of arclets beyond the radii of large arcs reveal clumpiness of the potential near some bright elliptical cluster members (Pello 1992, Fort 1992). The triple arc in 0024+1654, broken by a perturbation of a cusp by a group of such E galaxies, permitted a direct estimate of their masses (Kassiola, Kovner and Fort 1992). The steepness of the cluster potentials can also be probed statistically by the frequency of rings around individual cluster galaxies (Kochanek and Blandford 1991).

Probable redshifts of individual arclets can be roughly constrained from their ellipticity and orientations (Kochanek 1990, Miralda 1991). The colour redshifts of arclets (Fort 1992) and redshifts of luminous arcs (Mellier *et al.* 1991, Pello *et al.* 1992) are in agreement with the deepest redshift surveys of field galaxies. Spectrophotometry of magnified arc(let)s would have a large impact on the studies of evolution and formation of distant objects (Mellier *et al.* 1991, Smail *et al.* 1993). The spectacular HST observation of a gravitational pair of compact blue objects in AC114 (Smail *et al.* 1993) and of A370 (Kneib *et al.* 1993) at CFHT may offer the opportunity to study objects with (unmagnified) $B \sim$ 29-30 (Miralda and Fort 1993).

Arclets can constrain the general geometry of the cluster potential, although the method is limited by poor statistics and by the effects of intrinsic ellipticity and orientation of the sources (Tyson *et al.* 1990, Kochanek 1990, Miralda-Escude 1991 a,b, Kaiser and Squires 1993). Deep weak-lensing measurements have been already started up to 15 arcmin from the center of Cl0024+1654 and in a blank field (Bonnet *et al.* 1993). Such observations should improve spectacularly with the availability of large CCD mosaics, since large scale mass inhomogeneities can produce coherent distortions of a few percent in a pattern on a scale of $\sim 1°$, and should constrain cosmological models for LSS formation (Blandford *et al.* 1991, Miralda-Escude 1991 and Kaiser 1992).

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High Redshift Galaxies and Galaxy Evolution
(Matthew Colless)

This report provides an overview of research into high redshift galaxies and galaxy evolution from an observational perspective over the period 1990 to 1993. Only references to the literature from this period are given in order to provide a snapshot of current research. Several related topics (e.g. high-redshift galaxies as probes of cosmological models, galaxy interactions and evolution at low redshift, and gravitational lensing) are dealt with elsewhere in this volume.

Counts and colours of faint galaxies

The general form of the number counts of faint galaxies in passbands ranging from U to K has been confirmed by several studies[58] to very faint limits (B≈26–29, K=≈20–23). Good agreement is obtained in the overlap regime between the wide-field photographic studies to B≈23 and the fainter small-field CCD studies[56,78]. The number counts are steeper in the bluer bands and flatter in the red, corresponding to a general blueing of the galaxy population at fainter apparent magnitudes. This is directly observed in the colour-magnitude distributions[78,99], although these studies suggest that some earlier work[51] may have overestimated the degree to which the galaxies become bluer at the faintest magnitudes. The very steep, almost Euclidean, slope for the bright (B<20) number counts[72] has been corroborated. In general, the counts in the blue are found to be steepest at bright magnitudes and then flatten out at fainter magnitudes to be only slightly steeper than the red counts[68,99]. Upper limits on the number of $z\sim3$ galaxies have been derived from the scarcity of galaxies detected in B or R that are not detected in U due to the Lyman limit break[51,99]. A new development has been number counts in the K passband at 2.2μm. Complete counts[50] to K=17 and fainter counts[28,27] to K=23 have extended into the IR the trend to a flatter slope (and less evolution) fo- redder passbands.

At the faintest levels the surface density of galaxies becomes very high, reaching 10^5 deg^{-2} mag^{-1} at B≈26 and at K≈22. Some claims for a levelling off of the number counts at fainter magnitudes have been made[27], but these have yet to be confirmed. High angular resolution will be important in obtaining reliable results to yet fainter limits, as recent studies with the NTT[83] and HST[93] have shown.

Redshift surveys of faint field galaxies

Field redshift surveys[20,21] to B=22.5 showed that to this limit the bulk of the galaxies making up the factor of two excess in the number counts (compared to no-evolution models) are at rather low redshifts, typically less than z=0.5, and are not high-redshift primeval galaxies. The redshift distributions are similar to the no-evolution predictions, with no extra populations of local dwarfs or galaxies at high redshift, suggesting that the excess counts must result from a process resembling number density evolution. There is also a significant excess in the number of galaxies with enhanced star-formation, indicated by their [OII] equivalent widths[20,10]. Further magnitude-limited surveys[68,67,22,104] to B=24 and I=22 have extended these results, finding mean redshifts $\bar{z}\approx0.4$–0.6 and few galaxies with $z\geq1$.

The large excess of faint galaxies found in the counts together with the relatively low redshifts, particularly of the bluest objects, are difficult to reconcile with pure luminosity evolution of the galaxy population[68,21]. Possible problems with completeness and bias in the redshift surveys and an inadequate knowledge of the galaxy populations contributing to the luminosity function at low redshift have been cited as ways of reconciling the observations with mild luminosity evolution models[58,59]. Other authors invoke either a non-zero cosmological constant[113,67], strong merging of the galaxy population with associated star-formation[89,10], or a population of low-luminosity galaxies that go through a phase of rapid star-formation which is quenched by the exhaustion or expulsion of the gas supply, so that the objects fade beyond detection at low redshift[29,3]. High-resolution imaging of faint galaxies[49,67,23,104] suggests that interactions are a significant factor, but at present the nature of galaxy evolution at moderate redshifts remains an open question[58,52].

Galaxies in high-redshift clusters

There has been continuing interest in the properties of galaxies in high-redshift clusters. A second sizable catalogue of high-redshift clusters appeared[25], while several groups investigated the high fraction of blue galaxies in distant clusters (the Butcher-Oemler effect), both through photometric studies[87] and spectroscopically[36,37]. These studies confirmed the strong increase in the blue fraction with redshift and demonstrated that it is largely composed of emission-line and E+A galaxies that are much scarcer in clusters at low redshift. These galaxies appear to have been involved in recent or ongoing starbursts[37]. The Butcher-Oemler effect has also been studied in X-ray and infrared-selected cluster samples[47,2], confirm that the effect is not due to optical selection biases with redshift. Radio-selected groups[1] link the Butcher-Oemler effect in rich clusters to the field: all groups have a large blue fraction at high redshift, with the richer groups evolving most rapidly to redder colours at low redshift. There is now also evidence[36,2] for evolution of the *reddest* galaxies in clusters with z=0.5–1, with few cluster galaxies as red as present-day ellipticals by $z \approx 1$.

Some progress towards understanding the mechanisms of galaxy evolution in clusters has come from new high-resolution imaging, both from the ground[64] and from preliminary studies using HST[24,35]. These studies show a large fraction of the blue galaxies to be interacting, although whether interactions are the primary mechanism[64] or act jointly with ram pressure stripping and other effects[35] remains to be resolved. HST imaging has also turned up a serendipitous candidate for the highest redshift cluster[38]—a group of faint blue objects which may be associated with a QSO at $z \approx 2$.

Clustering of faint galaxies

Several recent observational studies[43,81,86,26,90] have determined the angular two-point correlation function $w(\theta)$ for faint galaxies with $B \lesssim 24$–26 and $R \lesssim 23$–24. The major finding of all these studies is a low $w(\theta)$ amplitude for such faint galaxies, with the blue galaxies more weakly clustered than the red. Although the observations are now well-attested, debate continues on their significance. Early claims that the low amplitude of $w(\theta)$ implied the faint blue galaxies were so weakly clustered that they could not be identified with normal galaxies at low redshift[43] have been disputed on the basis that the assumed evolution of gravitational clustering underestimated that actually observed in N-body simulations[77,114]. The other difficulty in interpreting these results lies in the unknown redshift distribution of galaxies at such faint magnitudes. Currently it is unclear whether $w(\theta)$ for faint galaxies can be entirely explained by strong evolution of clustering, or whether the faint blue galaxies are required to be at higher redshifts or more weakly clustered than expected. The deepest data on the *spatial* two-point correlation function $\xi(r)$ reaches $B \approx 22$ ($\bar{z} \approx 0.2$) and shows no evidence for weaker clustering[19].

High-redshift radio galaxies

The state of the controversy in 1990 concerning the age and star-formation history of high-redshift radio galaxies is captured by reviews in the Hubble Symposium[66,106,16]. The existence of an old (1 Gyr) stellar population was deduced from the SEDs and the small scatter in the K-z relation[66], putting the galaxies' redshifts of formation at $z \geq 5$. On the other hand, the 'alignment effect', whereby the optical and IR emission tends to be aligned along the radio axis, indicated a physical relation between the (young) radio source and the visible galaxy[8,16]. Other work showed that the spectra might also be consistent with younger ages[15,89].

Further imaging has supported the tendency for the IR continuum to align with the radio axis[44], but the elongation in the IR is generally less than in the optical, consistent with an aligned flat-spectrum component (contributing ~10% of the IR light) overlying a more symmetric red component[88,74]. This applies to 6C 1232+39, but for this object the blue continuum and Ly α are not contiguous as expected if they traced the star-forming regions[41]. Measurements[102,94] showing 5–20% polarization of the rest-frame UV continuum, aligned perpendicular to the radio axis, imply that a large fraction of this component is light scattered by dust or electrons from the AGN. Numerous models exist for the origin and scattering mechanism of this non-stellar light[30].

Recent work has shown that reddening and the contribution of emission lines have caused the IR flux (and hence the age of the stellar population) to be over-estimated[73,40]. In the case of B2 0902+34, at z=3.4, it is claimed that once corrected for such effects the SED is consistent with a galaxy observed during its initial burst of star-formation[42]. The lack of any 4000Å break in high-redshift radio galaxies also argues against the presence of an old stellar population[53].

Absorption line systems

The rarest QSO absorption line systems are the damped Ly α absorbers, which have high HI column densities ($N(HI)z \sim 2 \times 10^{20}$ cm^{-2}) and low velocity dispersions resembling those of present-day galactic HI disks[60,109,105,107]. The mass in these systems is comparable to the luminous mass in spiral galaxies today; however their incidence is 2–4 times greater than expected[60] if the size and number density of spirals were the same at $z \sim 2.5$ as at z=0. Abundances and dust-to-gas ratios in the absorbers are down by an order of magnitude compared to the local ISM[85,79]. The evidence for evolution in the properties of damped Ly α systems is weak[60], although an increase in the number density for $z \sim 3$ has been suggested[107]. Some galaxies

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associated with Ly α absorbers have been discovered through their Ly α, [OII], Hβ or CO emission[46,69,110,14,71], and appear consistent with large star-forming disks. Recent observations suggest that the clustering of Ly α-emitting galaxies around Ly α absorbers, and of the absorbers themselves, is strong over scales of several Mpc, in contrast to the weak clustering of faint galaxies[108,48].

Considerable observational effort has gone into the Lyman limit (LL) systems and metal line (MgII and CIV) absorbers which have column densities N(HI)$\sim 10^{15}$ cm^{-2}. Large samples have now been studied[61,100]. The MgII and LL systems show no evolution in comoving number density, but the CIV absorbers show strong evolution at z$\sim$ 2 due to a marked change in the strength of the line and the sample selection[100,98]. This may mark the era of halo formation[97], although contrary results indicate strong evolution of LL systems and CIV absorbers due to changes in the ionization level[61]. The complex velocity structure[63] of the line profiles on scales 50–300 km s^{-1} suggests either clouds within a halo or multiple smaller halos[62]. A decrease in the number of velocity components (clouds) at larger impact parameters is observed[62], supporting the halo model. The equivalent width of the MgII systems decreases with time[100], implying a decrease in the the number of clouds per halo[84]. The MgII and CIV systems are also clustered[84,100] on scales of several Mpc.

The galaxies associated with MgII absorbers have been identified[112,6,111] with a success rate of up to 80% and are generally bright, with L$\sim 0.2L^*$. The observed impact parameters to the QSO line of sight for the associated galaxies[6,100] are typically 30–50 h^{-1} kpc, although larger impact parameters up to 270 h^{-1} kpc have been found[112,80,39]. The former implies covering factors for the absorbing gas near unity; the latter much lower values. The impact parameter scales only weakly with luminosity[6,98]. By contrast, searches for MgII absorption in galaxies at known redshifts have failed in a significant number of cases, and find no deficit of fainter galaxies[5,39]. Recently the first z$\sim$1 galaxies associated with MgII absorbers have been reported[7]. These objects will undoubtedly yield important clues to the history of halo gas in normal galaxies[17,98], especially when low-redshift samples are further studied with HST[9].

Primeval galaxies

Despite extensive systematic searches[70,33,31], no population of 'classical' primeval galaxies (PGs, progenitors of normal luminous galaxies undergoing major bursts of star-formation at high redshift) has yet been identified. Several of these searches should have been able to identify 'classical' PGs out to z$\sim$5 if they were unobscured by dust[32].

Several examples of high-redshift galaxies not found through their radio emission or absorption line systems have emerged from searches for PGs[103] and gravitational lenses[75,4,76,82], and from studies of QSO companions[101,65] and hosts[54,55]. One particularly interesting object at z=2.3, F10214+4724, was first identified as an ultraluminous IRAS galaxy[91]. With an IR-dominated total luminosity of 10^3L*, and an H_2 mass estimated from CO observations[11,96] of $10^{12}M_\odot$, F10214+4724 appears to be a good PG candidate. Further observations have detected submillimetre flux[18], shown the H_2 to be extended[57,92,13] and detected large amounts of neutral gaseous carbon[12]. Although the estimated H_2 and dust masses have been revised downwards[34,95], the data still imply an enormous star-formation rate (1000 $M_\odot$/yr)[45].

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Results from the Cosmic Background Explorer (COBE) [1]

(G. F. Smoot and J. C. Mather)

Introduction

The structure of the Big Bang that started the expanding universe has been mapped for the first time by the Cosmic Background Explorer satellite (COBE). Designed, built, tested, launched, and analyzed by NASA's Goddard Space Flight Center and a nationwide science team[7], COBE captured the imagination with images of ripples in space-time, and tested the Big Bang theory with precise spectra of the heat radiation from the explosion. There are three main aims of the COBE: to find and measure the large scale fluctuations in the Cosmic Microwave Background Radiation (CMBR), to compare the spectrum of the CMBR with the theoretical prediction of a precise blackbody spectrum, and to measure or limit the cosmic infrared background radiation (CIB). These measurements are limited by foreground emissions. Interstellar free-free and synchrotron radiation, which perturb measurements of the CMBR anisotropy, are not well understood. Interstellar dust, which limits the precision of the spectrum distortion measurements, may include contributions from a cold dust component around 5 K with an order of magnitude more mass than the normal warm dust at 22 K. Interstellar ions and molecules, which emit in the far infrared, provide most of the cooling for the interstellar gas, and include the brightest emission line of the Galaxy (ionized carbon at 158 microns). Transiently heated dust grains and starlight show the structure of the Galaxy in new ways.

DMR and CMB Anisotropy

The origin of large scale structure in the Universe is one of the most important issues in cosmology. Currently the leading models for structure formation postulate gravitational instability operating upon a primordial power spectrum of density fluctuations. The inflationary model of the early Universe[2,21] produces primordial density fluctuations[22,24,39] with a nearly scale-invariant spectrum. Structure apparently forms as the result of gravitational amplification of initially small perturbations in the primordial mass-energy distribution, and non-baryonic dark matter seems necessary to provide sufficient growth of these perturbations. The determination of the nature of the initial density fluctuations then becomes an important constraint to cosmological models[8]. The discovery of the anisotropy in the cosmic microwave background radiation by the COBE DMR instrument[3,25,36,45] and the recent confirmation[18] mark the beginning investigation of these primordial fluctuations.

The Differential Microwave Radiometer (DMR) experiment is designed to map the microwave sky and find fluctuations of cosmological origin. For the 7° angular scales observed by the DMR, structure is superhorizon size so the spectral and statistical features of the primordial perturbations are preserved[32]. The DMR maps the sky at frequencies of 31.5, 53, and 90 GHz (wavelengths of 9, 5.7, and 3.3 mm). The frequency independence of the anisotropy is a strong argument that the anisotropy is in the cosmic microwave background radiation and not due to foreground Galactic emission or extragalactic sources. The confirming 'MIT' balloon-borne bolometer observations[18] have an effective frequency of about 170 GHz making the argument stronger. The typical fluctuation amplitude is roughly 30 μK or $\Delta T/T \sim 10^{-5}$ on a scale of 10° . The data appear consistent with a scale-invariant power spectrum with an uncertainty of ± 0.6 in the exponent of the power law. The amplitude and spectrum are consistent with that expected for gravitational instability models involving nonbaryonic dark matter, and perhaps consistent with the measured large scale velocity flows. The angular power spectrum of the DMR maps was also computed, and is consistent with other methods of analysis of the maps[48,49].

The cosmic nature of the measured fluctuations was tested[4] by correlating the DMR maps with maps of Galactic emission, the X-ray background, Abell clusters, and other foregrounds. The "blamb" structure reported by the Relikt team[40] is not present in the DMR map.

Several medium and smaller angular scale experiments have announced new results. These include: the UCSB South Pole experiment[17,35], the Princeton Saskatoon experiment[44], the Tenerife collaboration[27,42], the CARA South Pole experiments: Python[13], and 'White Dish'[33], the Center for Particle Astrophysics MAX balloon-borne experiment[12,19,30], the MSAM balloon-borne experiment[9], the Owens Valley Radio-astronomy Observatory (OVRO)[31], the Roma balloon-borne experiment ULISSE[11], and the Australia Telescope[41]. In

[1]The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the Cosmic Background Explorer (COBE). Scientific guidance is provided by the COBE Science Working Group. GSFC is also responsible for the development of the analysis software and for the production of the mission data sets.

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general, they report fluctuations at the 10^{-5} level. These measurements may distinguish models of structure formation or indicate the existence of cosmological gravity waves [10,37].

FIRAS and CMB Spectrum Observations

The Far Infrared Absolute Spectrophotometer (FIRAS) instrument compared the spectrum of the CMBR to that of a precise blackbody for the first time. It has a 7° diameter beamwidth, and covers two frequency ranges, a low frequency channel from 1 to 20 cm^{-1} and a high frequency channel from 20 to 100 cm^{-1}. Preliminary results[28] showed that the CMBR is consistent with a blackbody and that deviations are less than 1% of the peak brightness. The UBC rocket result[20] nearly immediately confirmed the FIRAS results. New FIRAS results show that limits on deviations from a blackbody are 30 times smaller: less than one part in 3000 of the peak intensity[14,15,29,47].

The absolute temperature of the cosmic background, $T_\circ$, was determined in two ways. The first uses the thermometers in the external calibrator and gives $T_\circ = 2.730$ K. The second calibrates the temperature scale from the wavelength scale, and gives 2.722 K for $T_\circ$. The adopted value is 2.726 ± 0.010 K (95% confidence[29]), which averages these two methods. Three additional determinations of $T_\circ$ depend on the dipole anisotropy. The spectrum of the dipole anisotropy is sensitive to the assumed blackbody temperature. Since the velocity of the solar system with respect to the CMB is not known a priori, only the shape and not the amplitude of the dipole spectrum can be used. For FIRAS, this analysis[14] gives $T_\circ = 2.714 \pm 0.022$ K, while for DMR[26] it gives $T_\circ = 2.76 \pm 0.18$ K. The DMR data analysis keeps track of the changes in the dipole caused by the variation of the Earth's velocity around the Sun during the year. In this case the velocity is known, so $T_\circ$ can be determined from the amplitude of the change in the dipole, giving $T_\circ = 2.75 \pm 0.05$ K.

The spectrum observations imply a tight limit on energy release in the early universe and strong support for the hot Big Bang model. From a redshift of about 10^6 to 10^3 no process can release electromagnetic energy at a level exceeding about 10^{-4} of that in the cosmic background radiation. Limits on the distortion parameters are $|y| < 2.5 \times 10^{-5}$ and $|\mu/kT| < 3.3 \times 10^{-4}$ with 95% confidence. The Comptonization parameter y restricts the possible thermal history of the intergalactic medium, which must not be very dense or very hot (less than $\approx$ 10 KeV). In addition, the FIRAS results limit energy release into the far infrared from Population III stars or evolving IRAS galaxies. In both cases, less than 1% of the hydrogen could have burned[47] after a redshift of 80, assuming $\Omega_{baryon}h^2 = 0.015$.

The FIRAS results can be combined and compared with other observations of the cosmic background spectrum. At this time the spectrum of the cosmic background is well described by a single temperature blackbody over four decades in frequency (or wavelength), without significant deviations. However, more precise measurements at long wavelengths could improve the COBE limits on μ by a factor of 10.

Non-cosmological results of the FIRAS include the determination of the mean far infrared spectrum of the Galaxy, and its decomposition into two components of dust emission and 9 spectrum lines[45]. The lines of [N II] and [C II] have been further interpreted[5,34].

DIRBE and the Cosmic Infrared Background

The primary objective of the Diffuse Infrared Background Experiment (DIRBE) is to conduct a definitive search for an isotropic cosmic infrared background (CIB), within the constraints imposed by the local astrophysical foregrounds, from 1 to 240 μm . Additional objectives include studies of the interplanetary dust cloud and the stellar and interstellar components of the Galaxy. Both the cosmic redshift and the reprocessing of short-wavelength radiation to longer wavelengths by dust act to shift the short- wavelength emissions of cosmic sources toward or into the infrared, and the CIB may contain much of the energy released since the formation of luminous objects. Measurement of the CIB would provide important new insights into issues such as the amount of matter undergoing luminous episodes in the pregalactic Universe, the nature and evolution of such luminosity sources, the nature and distribution of cosmic dust, and the density and luminosity evolution of infrared-bright galaxies.

The DIRBE approach is to obtain absolute brightness maps of the full sky in 10 photometric bands (1.2, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140 and 240 μm). To facilitate discrimination and study of the bright foreground contribution from interplanetary dust, linear polarization is measured at 1.2, 2.2, and 3.5 μm , using a combination of orthogonal polarizers and spacecraft rotation. All celestial directions are observed hundreds of times at all accessible angles from the Sun in the range 64 - 124° . The instrument has a large field of view, 0.7° square, and the sky signal is continuously chopped against a zero-flux internal surface. A cold shutter allows measurement of instrumental offsets and internal stimulation of the detectors.

The photometric quality of the DIRBE data is excellent; when the full reduction of the cryogenic-era data

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is complete, photometric consistency over the sky and over the 10 month period is expected to be near 1% or better. The instrument rms sensitivity per field of view in 10 months is λI_λ = (1.0, 0.9, 0.6, 0.5, 0.3, 0.4, 0.4, 0.1, 11.0, 4.0) $\times 10^{-9}$ W m^{-2} sr^{-1}, respectively for the ten wavelength bands listed above. These levels are generally well below estimated CIB radiation contributions and foregrounds.

Papers on the foregrounds have been submitted to the ApJ and presented[1,6,16,23,38,43]. Preliminary full sky maps at wavelengths from 1.2 to 240 μm have provided dramatic new views of the stellar and interstellar components of the Milky Way. The zodiacal dust bands discovered in the IRAS data are confirmed, and scattered near-infrared light from the same particles has also been detected. Starlight from the galactic bulge region, after correction for extinction, has been shown to have an asymmetric distribution consistent with a non-tilted stellar bar. The warp of the near and far infrared emission near the galactic plane is similar to that expected from previous studies of the stellar and interstellar components of the Galaxy. New upper limits have been set on the CIB all across the infrared spectrum, conservatively based upon the minimum observed sky brightness[23].

COBE Data Products Release

An initial set of COBE data products from all three instruments was released in June 1993, and a new data release in June 1994 will include all-sky DIRBE and FIRAS coverage, DIRBE polarimetry, FIRAS data from the low-frequency band, and the first two years' worth of DMR data. Additional data will be released in June 1995. Documentation and initial data products are available by anonymous FTP from nssdca.gsfc.nasa.gov with the username "anonymous" and your e-mail address as password. Change to directory [000000.cobe] and get the file aareadme.doc. Data and documentation may also be obtained on tape by request to the Coordinated Request and User Support Office (CRUSO), NASA/GSFC, Code 633.4, Greenbelt, MD 20771, phone: 301-286-6695, e-mail: request@nssdca.gsfc.nasa.gov.

Discussion and Summary

The COBE has been a remarkably successful space experiment with dramatic observational consequences for cosmology, and the DIRBE determination of the cosmic infrared background is yet to come. The very tight limits on deviations of the spectrum from a blackbody rule out many non-gravitational models for structure formation, while the amplitude of the ΔT discovered by the COBE DMR implies a magnitude of gravitational forces in the Universe sufficient to produce the observed clustering of galaxies, but perhaps only if the Universe is dominated by dark matter. The DMR ΔT provides measurement of the 'initial conditions' for the gravitational instability modes.

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RECENT PROGRESS ON THE DARK MATTER PROBLEM
(Bernard Sadoulet)

In last five years, considerable additional evidence[1] has been gathered on the fact that at least 90% of the mass in the universe is dark, by which we mean that it does not emit or absorb any form of electromagnetic radiation. Understanding this "dark matter" has become one of the more central problems in astronomy and cosmology. Once a subject of controversy among astronomers, its existence is now acknowledged by a large majority. The debate has shifted to the amount of dark matter in the universe and its nature. Its role in the formation of the large scale structure of galaxies is becoming a major study of cosmologists, and a number of observational tests have already limited significantly what it could be made of. Ambitious searches are starting, ranging from compact baryonic objects to elusive elementary particles which may have been produced in the Big Bang.

At the galaxy level, a large amount of dark matter is observed. In large spiral galaxies, it is often possible to measure[2] HI rotation curves out to many times the scale length characterizing the exponential decrease of the surface brightness away from the galactic center. The dark halo clearly dominates the dynamics and typical mass to light ratios $M(r)/L \sim$ 3-5 $M_\odot/L_\odot$ are obtained, increasing with radius even when no more stars are observed. Elliptical galaxies also contain large amounts of dark matter. While velocity dispersion measurement of stars probes a region where the dark matter is not dominant, the study of globular clusters[3] and of planetary nebulae typically show an increase of M/L from 3 in the inner part to 15 in outer parts. The extended X-ray emission[4] detected by X-ray satellites implies even larger values (>70).

The dynamic effect of dark matter is even more pronounced in clusters of galaxies. It has been known for some time that dispersion velocities of the many hundreds of galaxies which constitute rich clusters are often in excess of 1500 km/s. Such large values indicate very deep potential wells and M/L above 100. In many clusters[5], a large amount of gas is detected through its X-ray emission. There again, it is high temperature (~5 keV) X-ray gas which implies a similar depth of potential. In the last few years, a third piece of evidence has been gathered which also points to a very large amount of dark matter in clusters. Galaxy clusters gravitationally lens the light emitted by quasars and field galaxies in the background[6]. The mapping of the mass distribution through the many arclets seen in many clusters, indicates rather deep potential wells qualitatively similar to those observed with the two other methods.

The combination of all these observations makes it rather convincing that dark matter does indeed exist, unless the laws of gravity are violated on the large scale. If there is a wide consensus on this conclusion, there is still considerable debate on the amount of dark matter and the value of $\Omega = \rho/\rho c$, the ratio of the average density in the universe (which is dominated by the dark matter component) to the critical density. Summing the mass of individual galaxies and their halos leads to a value of Ω of the order of a few percent. The sum of clusters of galaxies gives $\Omega > 0.1$ to 0.2. It should be emphasized, however, that these methods are only able to give a lower limit on Ω, as they are insensitive to a smooth background density. Dynamic methods comparing the observed peculiar velocities to the density contrast are sensitive to the time available for acceleration and the growth of density fluctuations, and therefore to the value of the average density at the scale considered. Current measurements of velocity correlations and of velocity flows[7] hint at a large value of $\Omega(>0.3)$ at large scale. In principle, a correct measurement of Ω would have to rely on the measurement of the geometry. This is the aim of the classical cosmological tests. Although much more feasible than a decade ago[8] because of modern instrumentation, these tests continue to face the difficult problem of disentangling the geometry from the evolution of the standards used.

The average density is an important clue to the nature of dark matter. If $\Omega<0.1$, it may be made of ordinary baryonic matter, as that number of baryons in the universe is quite consistent with the measurement of primordial abundances of light elements and the standard nucleosynthesis scenario in a homogeneous universe. The attempts to circumvent this scenario by introducing inhomogeneities due, for instance, to a quark hadron transition have been so far unable to significantly change these limits[9]. If Ω is significantly higher, say greater than 0.2, we may be forced into the hypothesis that at least some dark matter is non-baryonic, that is, not made of ordinary matter.

Additional clues to the nature of dark matter may be obtained from the study of the large scale structure in the universe, formation of which is believed to occur through the gravitational collapse of primordial density fluctuations. It has been known for some time that dark matter is likely to play an important role and that

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in the simpler models it has basically to be non-relativistic (cold) at the time when density fluctuations begin to grow[10]. The opposite case, the so-called "hot dark matter" models[11] (based, for instance, on a light massive neutrino), lead to erasure of the density fluctuations on smaller scales by dark matter diffusion, and are not in qualitative argument with observations unless additional seeds (e.g., topological singularities) are introduced. The recent detection by COBE[12] of fluctuations in the microwave background temperature has brought even more interesting information. In the framework of primordial "adiabatic" fluctuations (i.e., initial fluctuations appearing in the same proportion in both the matter and photon components), the comparison of the COBE results with the density fluctuations observed in the large scale structure of the present universe[13] points to non-baryonic dark matter and roughly flat geometry (possibly through a non-zero cosmological constant). It is, however, possible to also account for the data, admittedly with more parameters to adjust, with baryonic dark matter in an "isocurvature" scenario[14] (where fluctuations in matter density are compensated by fluctuations in the radiation field).

As these considerations are likely to provide only indirect and somewhat model dependent indications, it is important to attempt to determine the nature of dark matter directly. A number of direct searches are already in progress.

In the case of baryonic dark matter, a number of possibilities are already excluded by observations.[15] The dark matter has to be in the form of condensed objects: brown dwarf or black holes. Both types can be combined under the name Massive Compact Halo Objects (MACHOs). Unless they are very massive, these objects can theoretically be detected by microlensing[16]: If one of these MACHOs happens to cross the line of sight to a star, say in the Large Magellanic Cloud, a temporary increase of the intensity will be observed. This increase would be symmetric in time, achromatic and non-repetitive, contrary to sporadic phenomena in stars. Three collaborations, Livermore-Center for Particle Astrophysics-Mount Stromlo, Saclay-Orsay-Observatoire de Paris-Observatoire de Marseille, and Princeton-Cracow, are now actively searching for such events, an effort which requires the regular observation of some ten million stars. Three microlensing candidates have been recently announced[17] by the first two collaborations.

As explained above, if $\Omega = \rho/\rho c$ is significantly greater than 0.1, we may be forced into the position that the dark matter is at least in part not made out of baryons. If we discard exotica such as a shadow universe or primordial black holes, the most attractive hypothesis then is that dark matter is made of particles that were created in the hot early universe and managed to stay around.

One of the well-motivated candidates is the axion. Such a particle has been proposed[18] in order to suppress the strong CP violation implied by the otherwise very successful Quantum Chromodynamics. It has not been observed, but it is interesting to note that the combination of laboratory and astrophysics experiments has constrained its mass in such a way that if it does exist, it must be cosmologically significant, accounting for a large fraction of the critical density. These "invisible" axions from the halo of our galaxy could in fact be detected through their conversion into monochromatic microwave photons inside a tunable microwave cavity in a large magnetic field. In the past ten years, two pilot efforts[19] explored the technology, but lacked about three orders of magnitude in sensitivity to reach a cosmologically interesting limit. A second generation experiment is currently in preparation at Livermore, which will begin to enter an interesting sensitivity range over one decade in mass (out of the three still allowed).

Without further information from a specific model, it is quite natural to assume that these dark matter particles were once in thermodynamic equilibrium with the quarks and leptons. In this case, their current density depends on whether they were relativistic or not at the time they decoupled from the rest of the universe. If they are light enough to be relativistic at that time, their density is just related to the decoupling temperature and is basically equal to that of the photons in the universe. This is, for instance, what is expected to have happened for light neutrinos, and a neutrino of 25 eV would give a Ω of the order of unity. Unfortunately such a neutrino is extremely difficult to detect in the astrophysical environment. It should be possible, however, to test this hypothesis in the laboratory once two neutrino oscillation experiments exploring this mass range are operational at CERN in 1994.

For particles which happened to have decoupled when they were non-relativistic, their density today is inversely proportional to their annihilation cross section[20]. A density close to the critical density leads to a cross section of the order of the Weak Interaction, indicating that the physics at the $W^{\pm}/Z^{\circ}$ intermediate vector boson scale (e.g., supersymmetry) may be responsible for the dark matter in the universe. This generic class of particles is usually called Weakly Interacting Massive Particles (WIMPs). A first generation of experiments[21] looking for elastic scattering of such WIMPs in the laboratory with solid state detectors proved that heavy Dirac neutrinos cannot be a major component of our galactic halo, and almost eliminated a class of WIMPs designed both to be dark matter and to account for the paucity of solar neutrinos. A second generation of laboratory experiments is being brought into operation; depending on the groups, they use larger masses of germanium detectors, large scintillating crystals of NaI, or novel "cryogenic detectors" working at millikelvin temperatures. While the first methods promise sensitivity gains of a factor 3 to 10, the cryogenic detectors allow an active rejection of the radioactive background (e.g., through the simultaneous measurement of the phonons and ionization produced in particle interactions[22]) and may give gains of one hundred or more. These experiments will begin to probe the rate region expected for the theoretically favored neutralinos, the lightest particles in supersymmetry.

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