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DIVISION VIII: GALAXIES AND THE UNIVERSE
(LES GALAXIES ET L'UNIVERS)

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Commission 28: Galaxies
Commission 47: Cosmology

1. Introduction

This report can touch on only the barest highlights of extragalactic astronomy during the past triennium. The last ten months of that period alone saw published in the standard archival journals nearly 700 papers with sufficient new information to deserve quotation. Some additional brief notes on the topics covered can be found in the reviews of the highlights of 2000 and 2001 (PASP 113, 1023; PASP 114, 475), and all references will be given in this very abbreviated form to maximize the number of topics that can be addressed.

2. The Cosmological Parameters

During a panel discussion at the end of Symposium 183 (part of the Kyoto General Assembly in 1997), several participants put up lists of their best estimates of standard parameters describing the present universe. Somewhat surprisingly, these lists were all very similar. Even more surprising, the best estimates as 2002 comes to an end have changed very little from those of 1997. Here is the list, followed by comments and references, plus a small subset of the dissenting votes.

- H = 65 $\pm$ 10 km/sec/Mpc (or h = 0.65)
- Ω (baryon) = (0.033 $\pm$ 0.013) h^{-2} (consistent with big bang nucleosynthesis)
- k = 0 $\pm$ 0.1 (that is, *Omega* = 1 $\pm$ 0.1, total and flat space)
- Ω (matter) = 0.3 $\pm$ 0.1
- $\Omega(\Lambda)$ = 0.7 $\pm$ 0.1 (or quintessence, with $P = -w\rho$ and $w \geq 0.7$)
- n = 1 (Harrison-Zeldovich spectrum of primordial fluctuations)
- age = 13 - 15 Gyr
- $\sigma_8 = 0.9 \pm 0.1$ (rms density fluctuations on scale of 8 h^{-1} Mpc)
- Ω (HDM) = 0.001 $-$ 0.01 (in neutrinos of small, non-zero rest mass)
- Ω (CDM) = 0.25 $\pm$ 0.05 (in WIMPs, axions, or other forms)

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Of these, perhaps the Hubble constant, H, has aroused the most controversy. A dozen or more values are published every year, ranging from about 40 to 85 km/sec/Mpc and deriving from a wide range of distance indicators, from familiar, traditional ones like Cepheid variables to arguments involving time delays in gravitational lensing and the Sunyaev-Zeldovich effect. The median values over the past few years of all numbers published in the 25 main archival journals have been: 60 (1998), 62 (1999), 64 (2000), 70 (2001), and 60 (first eight months of 2002). The final number from the Hubble Space Telescope Key Project Team was 72 $\pm$ 8 (ApJ 553, 47), with 58 $\pm$ 6 from a parallel independent HST effort (AJ 123, 123).

The other numbers, including the density parameters, k, age, and the deceleration parameter, q_0, come from various combinations of data on medium-scale fluctuations of the intensity of the cosmic microwave background radiation, apparent distances to Type Ia (nuclear explosion) supernovae, and large-scale distributions of galaxies and clusters, with additional constraints from the ages of the oldest stars and radioactive elements, and the primordial abundances of helium, deuterium, and lithium. Different observation sets have greatest sensitivity to different parameters, but nearly all the results are reasonably, mutually consistent (apart from a brief false alarm arising from a high baryon density implied by some incomplete CMB data, ApJ 545, L1). With these numbers, the turn-around from a decelerating to an accelerating universe happened fairly recently ($z = 0.4$ - 1.0) and galaxies with large redshift are now receding faster than the horizon, so that a message now sent to $z = 1.8$ will never arrive, and we will never see a $z = 5$ galaxy at an age larger than 6 Gyr (Nat. 415, 374).

To see how all the data come together to give these best estimates, we recommend starting with the mini-reviews (Sci. 284, 1503, Sci. 284, 1481). Good updates are ApJ 536, L59, ApJ 536, L63 (CMB data), A&A 356, 418 (large scale structure), ApJ 534, 565 (X-ray clusters), MN 310, 565 (normalization of density fluctuations), Nat. 405, 143 (weak lensing), ApJ 536, L85 (thorium age), Sci. 292, 2302 (connecting CMB fluctuations to galaxy distributions), Nat. 410, 169 (galaxy distributions from the new 2dF survey), MN 321, 333 (synthesis of all three main sorts of data), ApJ 651, L7 (MAXIMA CMB data), ApJ 564, 559 (BOOMERANG), and ApJ 565, 46 (DASI).

Some published numbers lie outside the consensus range described. Most rely on some limited data sample, e.g. Ω (baryon) = 0.14 from a few X-ray clusters (MN 311, 825), Ω (matter) = 1 from the K-magnitude redshift relation for radio galaxies (MN 329, 277) or the distribution of QSOs in 2dF (MN 332, 311), and Ω (matter) not more than about 0.22 from other X-ray clusters (ApJ 565, L5). An enormously useful set of equations relating the parameters and measured values of apparent magnitude and angular diameter vs. redshift is found in ApJ 565, 1. Earlier published versions of these nearly always assume zero cosmological constant.

Still further outside the consensus range are papers and their authors advocating something considerably different from a hot big bang universe based on general relativity. Among those of longest standing are the steady state and quasi-steady state universes (ApJ 525, 10; AJ 199, 2583) with their apparent need for an age-related or other non-cosmological component to measured redshifts (ApJ 565, 681, ApJ 566, 705) as well as continuous creation (ApJ 567, 801); MOdified Newtonian Dynamics, MOND, in which there is a minimum acceleration possible (ApJ 561, 550, PRL 83, 3990, ApJ 533, L99, MN 313, 767), and several versions of quantized or periodic redshifts (Astron. Lett. 23, 549, A&A 385, 431, Ap&SS 370, 308, which are not the original ideas but contain entres to the earlier literature). In any case, it is impossible not to love ApJ 571, 615, in which subtraction of the non-cosmological portion from the redshifts used by the Key Project Team to find a Hubble constant near 70 km/sec/Mpc leaves the corrected value of 55 km/sec/Mpc very close to that advocated by the other team. And yes, the author is H. C. Arp, the only colleague whose name we will mention explicitly in these pages.

3. The Black Hole Bulge Connection

In the era of the post-fix HST, central black holes have changed from being the rare possession of obviously active galactic nuclei to being the common property of virtually all galaxies. An important correlation is that between the mass of the central black hole (found from stellar or gas dynamics or reverberation time or other arguments) and the mass of the bulge or spheroid part of the host galaxy (best found from the central velocity dispersion but also from luminosity if nothing else is available). The mass ratio is about 10^{-3} and has been found independently from a very large number of data samples (AJ 115, 2285, ApJ 539, L9, ApJ 539, L13, ApJ 543, L5, MN 320, L30). Galaxies like M33 with no detectable black hole and tight limits also have no bulge population to speak of (AJ 122, 2469). The ratio is more or less the same for active galaxies as for quiescent ones (ApJ 565, 767 and MN 331, 795 on Seyfert galaxies, ApJ 569, L35 on Blazars), but on average a factor three higher (in the sense of more black hole for a given bulge) in radio loud sources (MN 327, 159). Of the moderate number of dissenting votes, we note only the alternative correlation, with black hole mass proportional to $M_{\rm bulge}^{1.74}$ (A&A 380, 31).

Now, why should this correlation exist? Many of the early models (see PASP 111, 385, Sect. 9.1) proposed either that the bulge controlled formation of the black hole or conversely. Most of the more recent ones have involved some sort of co-formation (except perhaps for Astron. Lett. 27, 759, which starts with primordial black holes of 10^5 solar masses, and A&A 379, L39, which starts with a dense star cluster). A subset of these models and what seems to be the dominant physics includes self-interacting dark matter (PRL 84, 5258 and ApJ 572, 41), radiation drag (ApJ 560, L29; MN 329, 572), observational evidence for co-formation (Sci. 294, 2549), mergers (MN 313, L29, ApJ 557, L19, ApJ 552, L13, MN 311, 576), spin of the dark matter halo (MN 311, 279), degree of central condensation of the galaxy (AJ 122, 1707, MN 329, 572), monolithic collapse (ApJ 551, L31), wind ejection of cold gas (MN 308, L39), and a self-gravitating disk around a black hole (ApJ 551, L151).

4. The End of the Dark Ages: Re-Ionization and the Missing Baryons

The first spectrum of the first quasar (3C 9) with a redshift close to two made clear that the present universe contains very little truly diffuse neutral hydrogen gas. Starting with the hot dense universe, on the other hand, reveals that the total baryon density must be about 6×10^{-32}g/cm^3 to account for the observed abundances of helium, deuterium, and lithium (ApJ 552, 718, ApJ 551, L1) and that these baryons must have gone from being ionized at redshifts greatly in excess of 1000 to being neutral at redshifts less than 1000 ("recombination") to being in some combination of stars, structured, and diffuse gas at the present time. The "big" questions are (a) where are most of the baryons now? and (b) if there has ever been a significant diffuse component (hard to avoid at large redshift) when were the baryons reionized and how? The triennium just ending has, apparently, seen the answer to both of these.

The present baryons of course include the stars in galaxies, gas at various temperatures within the galaxies, and quite a lot of hot (10^8 K roughly) gas in X-ray emitting clusters of galaxies. But these add up to only about 25% of the expected total. As recently as a redshift of 4, most of the rest was in structures that we detect as absorption features in the spectra of more distant QSOs (ApJ 550, 26, ApJ 559, 507, A&A 379, 393). Now theorists have been telling us for some time that these structures have continued to evolve into sheets and filaments of gas surrounding and tracing more obvious large scale structure, but with density enhancements of factors of only 10 – 350 (vs. 10^6 for a typical large galaxy) and temperatures of 10^{5-7} K (ApJ 552, 473, ApJ 559, L5). It seems that they were right. This so-called warm/hot intergalactic medium (WHIM) has now revealed itself as a source of both absorption and emission lines of multiply ionized oxygen (ApJ 573, 157 and ApJ 572, L127, and, somewhat less directly, AJ 123, 1953, ApJ 564, 637, and ApJ 561, L31). Such gas must inevitably contribute to the soft (less than 1 keV) X-ray background (ApJ 548, L119, ApJ 551, L139, ApJ 557, 67, ApJ 552, 473, ApJ 569, 595) and indeed may already have been shown to do so (ApJ 565, L13). The WHIM should also cause intergalactic scintillations of radio sources (MN 325, 1643). Not seeing the expected soft X-rays or scintillations would, of course, be worrying.

Now, when was the gas re-ionized, and where did the photons come from? The critical data are a set of three spectra of QSOs found by the Sloan Digital Sky Survey at redshifts of 5.3, 5.73, and 6.28. Space just blue-ward (that is, closer to us) of the first is essentially transparent, the second has a few narrow windows of transparency, and the light from the third meets completely opaque gas very close to itself, causing a trough of absorption just blueward of the Lyman-alpha emission line (ApJ 560, L5, AJ 122, 2833 & 2850, AJ 123, 1247). That is, we have directly seen the reionization of (most of) the hydrogen. Similar troughs at the wavelength expected from He II were found several years ago, and they and other data are consistent with re-ionization of helium having been completed at $z = 3 - 4$ (MN 332, 601, MN 332, 667, ApJ 567, LI03) compared to $z = 6$ for hydrogen.

Two main sources for the ionizing photons have been suggested: very early active galaxies and very early formation of massive, blue stars. These latter will not much resemble the OB stars of today (ApJ 562, L1, Sci. 295, 93, ApJ 551, L27, MN 317, 175), having masses of 100 solar masses or perhaps much more, little or no opacity due to metals in their atmospheres, and so forth. Some models find that QSOs will dominate (ApJS 130, 67, ApJ 549, L11) at least at larger redshifts, while others favor stars at all times (ApJ 549, L151, ApJ 552, 464, ApJ 546, 665). Because QSOs typically have power-law (non-thermal) spectra, while stars are nearly black bodies, the residual ratio of He II/H I in partially ionized clouds, like those of the Lyman-alpha forest, should provide a signature (larger ratios meaning the softer photons of stars). There does not seem yet to be a large enough number of forest lines measured at redshifts in excess of 5 to say much, but at the intermediate redshift range ($z = 2.3 - 2.85$) clouds suggestive of the two types of ionization are about equal in number (Sci. 293, 1112).

5. Cooling Flows

Cooling flows to where? we asked some years ago (PASP 107, 1, Sect. 10). What this meant was the analysis of X-ray images and spectra of rich clusters of galaxies showed that the central cooling times for the hot gas were considerably less than a Hubble time, implying that the gas should be cooling and turning into other forms (neutral gas, molecular gas, perhaps dust, and new stars) and yet none of these were seen at the centers of the clusters in amounts even remotely able to accommodate the rates at which cooling flow gas seemed up to arriving, up to 1000 solar masses per year. ROSAT was able to follow a bit of the gas down to 10^{5-6} K without finding much (ApJ 532, L113), and the X-ray community was made acutely aware of the problem when spectrophotometry from the Chandra and XMMNewton satellites made clear that gas below about 1 keV was truly very sparse at the centers of virtually all the standard cooling flow galaxies.

The current observational situation is this: (a) there is very little sub keV X-ray gas or excess absorption in a number of clusters (A&A 386, 77, ApJ 573, L131, A&A 365, L99, ApJ 567, 130), (b) there is little in the way of traditional HII (10^4 K) gas (ApJ 560, 134, ApJ 569, 134, AJ 119, 1123), (c) there is very little CO (PASJ 52, 235), perhaps 5-10% of the expected amount (MN 328, 762) and little or none of the dust that might be expected to accompany molecular gas (A&A 383, 367), (d) intermediate temperature gas responsible for UV-emitting filaments can account for a through-put of perhaps 10^{-3} solar masses per year rather than 10^{+3} (AJ 123, 1357, ApJ 560, 180), and (e) there is also sometimes evidence for a bit of current star formation, but, again, not much (MN 327, 1057).

Not surprisingly, a good deal of recent effort has gone into trying to reconcile the discrepancies. In some cases, re-examination of the X-ray data per se results in a much-reduced estimate of the expected inflow (ApJ 560, 184, ApJ 569, L27) bringing it within observational limits. But the main thrust has been a search for ways of reheating the gas from either center or outside, so that the observed configurations actually last a Hubble time (averaging over the various appearances a cluster might have). Conduction is one possibility

(ApJ 562, L129). More popular are mergers, which will surely disrupt any coherent flow, a well as heating the gas (A&A 377, 428, ApJ 561, 621, ApJ 562, 254, MN 329, 675, ApJ 569, 122, MN 331, 1011). But the strategy that has inspired the largest number of papers has been consideration of the effects of a central active galaxy, jets coming from it, black hole binary mergers, bubbles of non-thermal radio emitting gas, and so forth (Nat. 414, 425, A&A 378, 408, MN 328, 1091, Sci. 296, 1040, ApJ 563, 103, ApJ 563 , 95, ApJ 562, L149, ApJ 562, 618, A&A 382, 804, ApJ 567, L27 & L37, MN 331, 545, MN 322, 271, ApJ 571, L13, MN 332, 729, Nat. 418, 301, MN 333, 145). It has been noted that radio jets are less likely to damage composition gradients than are mergers (ApJ 571, L13). Indeed, highly relativistic electrons from a central engine could add non-thermal emission to the mix, much reducing the estimates of cooling flow throughput (ApJ 567, 762). Neutralino decay is another possible central heat source (ApJ 562, 24), as is the rotation of the cluster (A&A 382, 864). Including more than one heating mechanism is perhaps a better choice (A&A 383, 450, MN 331, 1011).

Several speakers at IAU Symposium 214 (whose proceedings should appear at about the same time as this volume) suggested that the so-called "cooling flow problem" could be regarded as solved by the combination of new data and multiple sources of reheating. This is perhaps too strong a statement. Some observed clusters unquestionably combine relaxed appearance and strong composition gradients with gas that cools toward the center and has an expected lifetime much less than the Hubble time (ApJ 565, 195, ApJ 567, 772, MN 331, 273, MN 331, 635, MN 332, L50).

6. Background Radiation

Some unresolved flux has been seen at all observable wavelengths and frequencies. Starting at 1 MHz and continuing through the radio band, that flux is heavily dominated by emission from our own galaxy (Astron Lett 26, 533 on 1 MHz data) and belongs to Divisions VI and VII. Around 1 mm, the cosmic microwave background is responsible for most of the photons. Data are consistent with its temperature having been larger in the past in proportion to $(1 + z)$ as expected (A&A 381, L64), and the implications of fluctuations in its intensity across the sky are noted in Sect. 2.

The flux in the submillimeter regime comes mostly from dusty, ultraluminous infrared galaxies at redshifts around 2.5 to 3 and has been largely resolved into sources (A&A 360, 1, MN 330, 92, MN 331, 495). The far infrared background could have significant input from AGNs (ApJ 566, L67), but the mid-infrared (15μ) does not (ApJ 568, 470, MN 332, L11). But perhaps the most important thing to be said about the supply of infrared photons between galaxies is that it is larger than is entirely consistent with TeV gamma rays reaching us from even the modest redshifts of Mkn 501, 421, and perhaps other active galaxies at z up to 0.4 (A&A, 359, 419, A&A 350, 757, A&A 371, 771, ApJ 544, 81, ApJ 543, L39, ApJ 560, L45). A clever solution involving a Bose-Einstein condensate of the high energy photons turns out not to be correct (ApJ 556, L21).

There are two ways of getting hold of the optical radiation density of the universe. One is to add up all the galaxies you see. This leads to $2.16 - 2.5 \times 10^8\ h\ L_\odot/\mathrm{Mpc}^3$ (AJ 122, 1104, MN 324, 825, MN 329, 579), a number remarkably close to that found by Jan Oort many decades ago (and implying the need for a mass to light ratio of somewhat more than 1000 in solar units if you want to close the universe with some form of matter). The other way is to look between the galaxies. This has just been accomplished successfully for the first time (ApJ 576, 56), yielding a value of 100 ± 20 pW/m^2-sr. The present author will gladly offer a complimentary glass of wine at the Sydney GA to any reader who can convert one set of units to the other and decide whether the numbers are roughly consistent. This radiation must come from some combination of stellar radiation and black hole energy extraction. The implications for the former are explored in ApJ 576, 56 and include consistency with the present average heavy element abundance of the baryonic universe, and the implications of the latter in ApJ 565, L75, and include the conclusion that black hole energy extraction must be fairly efficient, suggesting Kerr black holes and not much loss in Advection-Dominated Accretion Flow (ADAF).

The ultraviolet background is a bit difficult to get hold of by direct observation, since the extragalactic component is only about 5% of what we see (ApJ 563, L161), most of it being scattered galactic light. Two indirect methods are anyhow consistent. These are examination of the sharp edges of HI disks of spiral galaxies (AJ 122, 2428) and the so-called proximity effect. This means that the numbers of absorption lines in QSOs drops off at redshifts close to that of the QSO because ultraviolet from the QSO itself ionizes away nearby gas. The amount is thus a probe of the ratio of the QSO UV (which we see redshifted into the visible band) to the background UV (the quantity we want, ApJ 560, 101). If you want a number AJ118, 1450, gives 3400 photons cm^{-2} s^{-1} or 1.3×10^{-13} erg/(cm^2-sec-Hz-sr), and no we haven't checked for consistency of units.

In any case, the observed or implied UV background can generally be accounted for as the sum of AGN emission (ApJ 560, 103, ApJ 565, 773, ApJ 568, L9) with perhaps some additional contribution from hot stars. Notice that this is the same mix mentioned in connection with reionization (Sect. 4) and raises the same issue of what fraction of UV radiated by the hot stars in galaxies or pre-galactic fragments will actually get out, since these galaxies are just the ones where you expect to find a good deal of gas and dust to absorb and scatter. What fraction of the UV gets out? You might think this would be easy to decide. Just look at some favorite galaxies and add up the UV you see and the reradiated dust infrared that you see and compare them. The trouble is that neither is likely to be isotropic, and we cannot observe any one galaxy from more than one direction. Thus answers range from 10% or less getting out to two-thirds or more, without being really discordant (ApJ 559, L105, ApJ 565, L79, MN 331, 413, A&A 386, 801, ApJ 571, L107).

When it was first seen in 1962, the X-ray background was widely attributed to free-free emission by hot intergalactic gas. This was finally ruled out as the dominant process when the very accurate COBE spectrum of the CMB showed none of the distortions that such gas would produce. The present situation remains somewhat unsatisfactory, in large measure because of the great difficulty in calibrating the absolute flux values recorded by various X-ray satellites for both sources and continuum and in comparing absolute values from one satellite to another. Suffice it to say that as much as a quarter of both the soft (ApJ 560, 544) and hard (ApJ 566, L5) backgrounds could still be truly diffuse and presumably the product of the WHIM (Sect. 4), but it could also be essentially all the sum of sources, including both faint (and probably optically obscured) AGNs and star-forming galaxies. A very large fraction (but whether this is 75% or 100% is still under discussion) has actually been resolved by Chandra and other recent missions (ApJ 560, L19, MN 327, 499, ApJ 562, 42, MN 329, L18, ApJ 564, L5, ApJ 564, L65, ApJ 566, 667, A&A 389, 93, ApJ 570, 502). If you would like a number, the 2-8 keV background flux is about 2×10^{-11} erg/(cm^2-s-deg^2) according to ApJ 566, L5.

The gamma ray background, whose spectrum and fluctuations are much less well known, is also generally thought to be the sum of sources (ApJ 537, 763, MN 312, 177), but there is minority support for a diffuse, inverse Compton mechanism (Nat. 405, 156).

7. Very Large Scale Structure and Streaming

When all the problems of extragalactic astronomy have been solved, the topics of this section and the next two (star formation as a function of redshift and top down vs. bottom up scenarios for galaxy formation) will all be part of a single, coherent story taking us from a redshift of perhaps 100 down to the present and incorporating observations and calculations of the dynamical, morphological, and chemical evolution of galaxies as well. This has not yet happened, and cannot be anticipated in the next triennium or two either. Thus each gets a separate discussion, with at most weak linkage.

The largest-scale question is whether the universe continues to show ever-larger structures as you look at ever-larger samples, or does it turn over to homogeneity and isotropy?

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This can be made to sound more profound by asking it in the form of whether the universe is fractal. The answer seems to be no (PASP 112, 434 Sect. 12.3, with a slightly out-of-triennium paper ApJ 509, 531 showing that fluctuations in the X-ray background just nicely fill in the gap between the distribution of galaxies and the fluctuations in the CMB, where a fractal or hierarchical distribution is turning over to homogeneity and isotropy). Papers within the triennium have tended to confirm this (A&A 351, 405, MN 310k, 1128).

On the scales from galaxy pairs to rich clusters the correlation function $\xi(r)$ seems to have settled down to a power law very close to $r^{-1.75}$ (MN 309, 89, ApJ 571, 136) and a consistent projection onto the plane of the sky, generally called $w(\theta)$, for which new results from SDSS agree with those from earlier surveys without even the need for renormalization (MN 333, L21). Red galaxies are more strongly clustered than blue ones (MN 332, 617) and bright ones more strongly than faint ones (MN 332, 827). These appear in the constant in front of the power law, not its slope. The amount of clustering has increased with time (ApJ 572, 140), as one would expect in a "bottom up" or hierarchical universe (MN 314, 546, MN 310, 540). And, at least in a general sort of way, Abell clusters, radio galaxies, X-ray clusters, and the APM survey all trace more or less the same structures (ApJS 140, 239, AJ 122, 2222, Nat. 416, 150, AJ 123, 37 & 51). The mean size of a void in the galaxy/cluster distribution is about $30h^{-1}$ Mpc (ApJ 564, 641) or perhaps only 20 h^{-1} Mpc (MN 330, 399, well, after all it is a smaller journal). There is also general agreement that the local Hubble flow is quite "cold", indeed that the fluctuations around smoothness are smaller than the standard models of structure formation lead us to predict (PASP 114, 475, Sec. 12.4, A&A 378, 729, ApJ 564, 15 on biasing, A&A 383, 125, AJ 123, 2159).

Least concordance is to be found on the issues of what is the largest-scale structure to be found and whether there is any periodicity on that scale. About 200 Mpc say ApJ 541, 519 and MN 314, 375. As much as 400 h^{-1} Mpc for QSOs says MN 329, 336 (compared to at least 250 h^{-1} Mpc expected from various models, ApJ 566, 36, which does not seem to be a major discrepancy). But the authors of AJ 123, 37 & 51 continue to find periodicity at 120 h^{-1} Mpc which others have rejected (A&A 355, 900). It should come as a surprise to no one that theorists can account for such periodicity if required to do so (A&A 358, 1, MN 314, 256, A&A 358, 395). The largest things locally are the Great Attractor (A&A 380, 441, A&A 387, 1) and the dipole in the CMB (Astron Lett. 27, 765, Nat. 416, 150), and the former does not seem to be responsible for the latter.

8. The Redshift History of Star Formation

The obvious questions include (a) when did the very first stars form?, (b) when did most stars that we now see form?, (c) can star formation be associated with causal events like mergers?, (d) is it otherwise episodic in time and space or fairly smooth? That the answers to these would be somewhat complex (and coupled to the material of Sect. 9) became clear when systematic searches for "primordial galaxies", meaning a single episode that made most of the stars of a whole giant elliptical galaxy, failed (PASP 108, 8, Sect. 8). What was found instead (PASP 109, 78 Sect. 12) was extended star formation over the period $z = 1 - 3$ and more, typically occurring in entities many of which would have to be merged together to make a modern gE. The first, classic plot that put it all together, in units of $M_\odot$/yr-Mpc^3 (for which values over the years have ranged from less than 0.1 up to a peak of at most 1.0) appeared in 1998 (ApJ 498, 106). A major advance was the addition of submillimeter data (PASP 111, 385, Sect. 8.7) which made it possible to take better account of star formation hidden by dust. Moving into the present triennium, triggering by a whole range of processes, from complete mergers of clusters and galaxies down to individual supernovae and stellar wind shocks has come to seem more important (PASP 112, 434, Sect. 8.6, ApJ 561, 727).

Only for the Milky Way and its nearby dwarf companions can we look at individual stars and learn something of their masses and ages. Very crudely, the lessons are that on fine enough scales of time and space, star formation is localized and episodic (no real surprise; it doesn't take many OB stars and supernovae to disrupt a giant molecular cloud), while it looks smooth when averaged over a large part of a large galaxy (AJ 122, 1796, AJ 122, 2318, AJ 122, 2490, AJ 122, 2524, MN 329, 556, ApJ 562, 239, AJ 123, 813, AJ 123, 3141, MN 332, 91).

On all larger scales, we must use indicators, which inevitably can pick out only the short lived OB star contribution (since from 1 Mpc or more away, all G stars look pretty much alike). Thus quoted star formation rates (a) will be biased one way or another by the indicator chosen and (b) will have folded in some assumption about the IMF. Indicators in recent years have included the Lyman continuum (AJ 122, 1788), the submillimeter continuum (ApJ 561, L45), X-rays (meaning the ones from X-ray binaries and supernova remnants MN 328, 126), GHz radio emission (SNRs again mostly MN 330, 621), and the infrared, especially from space (MN 330, 876, A&A 382, 60), as well as the most traditional, H-alpha emission (MN 330, 876). In general rates derived from infrared data exceed those from H-alpha, which in turn are larger than the UV rates (A&A 383, 801), indicating, of course, dust absorption. It is, however, important not to overcorrect for this, as has sometimes been done, leading to enormous star formation rates at large redshift (MN 331, 283).

The current rate is supposed to be 0.022 ± 0.004 $M_\odot$/yr-Mpc^3 (MN 329, 227). Integrated over 15 Gyr, this would give a density of 8×10^{-32}g/cm^3 in stars and their remnants, which is about 0.4% of the closure density (far short of the total baryonic component, but you knew that).

Star formation began as early as $z = 8$ (AJ 123, 2151) or 10 (ApJ 564, 73), and a large fraction of the stars now found in the largest elliptical (ApJ 561, L37), and spiral (ApJ 562, L35) galaxies and in QSO hosts (MN 329, 149) existed as stars before $z = 1.5$ (ApJ 567, 672) and a third of spheroid stars by $z = 3$ (ApJ 564, 73). It is not, however, guaranteed that these stars were in whole galaxies ancestral to the ones we now see. Many field E and S0 galaxies, for instance, seem to have had both early and late ($z < 1$) formation episodes (ApJ 564, L13), and the latter might well have been associated with final assemblage of the galaxy from smaller (perhaps disky and definitely still gas rich) substructures. At least a few entities actually had star formation rates of 1000 $M_\odot$/year or more at $z > 1.5$ and so would meet the original definition of "primordial galaxies," except that it took SCUBA to see them (MN 331, 817). One recent version of the history gives SFR proportional to $(1+z)^{4.5}$ back to $z = 1$, flat from $z = 1$ to 2, and then declining as $(1+z)^{-1.5}$ beyond that. Less spectacular change, with SFR ($z = 1$) only three times the present value is given in ApJ 569, 582.

A very large fraction of the members of Commission 28 work on issues like stellar populations and chemical and morphological evolution of galaxies that might logically have formed part of this section. Progress in these areas (like star formation integrated over a whole galaxy) appears to be steady rather than saltational. A subset of the advances of the triennium are discussed in PASP 113, 1025 Sect. 8 and PASP 114, 475, Sect. 11. Present and future ones will appear in Symposia 217, 220, and 221 and Joint Discussions 21, 15, 10, and 11 at the Sydney General Assembly.

9. Galaxy Formation: Top-Down (Monolithic) vs. Bottom-Up (Hierarchical) Scenarios

For many years, astronomers have attempted to address a question of the general form: "Does the formation of galaxies and other structures begin with little things (meaning 10^8 $M_\odot$ or less) in a scenario called bottom up or hierarchical, or with big things (meaning cluster-sized entities or more) in a scenario called top-down or monolithic?" This was arguably a well-posed question with a potentially definitive answer for as long as the universe was thought to be made mostly of baryons (plus photons and neutrinos) and the dominant process was the conversion of gas to stars. The search for protogalaxies, undergoing a single, major, early burst of star formation was part of that picture. That most of the mass of most galaxies is in some form of non-baryonic dark matter has been part of the consuetudinal universe for a couple of decades. That one of the implications is that "top down vs. bottom up" may no longer be a clear dichotomy has taken longer to recognize and arguably belongs to the present triennium.

It is, for instance, entirely possible for underlying potential wells of dark matter to grow in a bottom-up pattern (ApJ 544, 6), while most of the star formation is deferred until the wells have grown to modern galaxy masses and the gas can experience a monolithic collapse (MN 318, 658). One could also imagine the converse, with most of the star formation occurring early in small entities that occupy shallow wells, while the underlying dark halos then experience something like monolithic collapse. In fact, once one accepts that the correct answer to the supposed dichotomy is likely to be "both, please", the most likely alternative seems to be that the two sorts of processes occur together for both the halos and the baryons. A sort of prediction of this point of view is that star formation should occur rather uniformly over much of the past of the universe, for which there is a good deal of evidence (ApJ 548, L147, MN 319, 168, ApJ 558, L31). One is also led to expect (or at least is not surprised) that there should be a few halos in which almost no star formation has taken place, though their masses (velocity dispersions; production of gravitational lensing) are comparable with those of other clusters (ApJ 557, L89) and that there do exist shallow potential wells at redshifts of 4-5 that act a bit like protogalaxies were supposed to, but are only about 1% as bright, because they are not forming stars for a whole, modern galaxy (ApJ 557, 527, ApJ 545, L85).

On the theoretical side, virtually all models of galaxy and structure formation now start with something like a Harrison-Zeldovich spectrum of fluctuations in the dark matter substrate and follow it forward in time, with some prescription for how the baryons react (MN 316, 374 compares 13 such models). The baryon physics is typically incomplete in its treatment of gas cooling, feedback from supernovae and AGN jets, and so forth. There is not yet general agreement on the masses of the entities that actually form most of the first stars. Things of $10^6 M_\odot$ start contracting first, as early as a temperature of 9000K, but may be overtaken by $10^8 M_\odot$ units that start later but evolve faster (MN 330, 927). Globular clusters may come first, at redshifts of 10 and larger, in their own halos, of which handfuls later merge to become dwarf spheroidal galaxies (ApJ 566, 245).

Interpretation of recent observations is similarly ambiguous. For instance, (a) the chemical evolution of giant elliptical galaxies is consistent with most of the stars having formed during monolithic collapse of the whole baryon ensemble (A&A 388, 396), (b) the systematics of globular clusters in disk galaxies (compositions, velocities, etc.) are claimed as supporting a top-down picture by ApJ 573, 122, (c) while the clusters of the Milky Way are described as coming in subsets from individual capture events (Sci. 297, 578) in a way that accounts for the traditional Oosterhof types of clusters, and some other dynamical families in the halo may have been found by the authors of ApJ 564, 736, (d) a hierarchical picture best fits the globular clusters of the galaxies in Hickson compact groups, which formed before the groups assembled (ApJ 567, 679) and the blue compact galaxies, whose masses have increased a factor of four since $z = 1$ (MN 329, L53), (e) related evidence says that there are no underlying old stellar populations in the compact, star-forming objects at $z = 2.0 - 2.5$ (AJ 123, 3041) and that the disk globular clusters of the Milky Way were made in gas-rich dwarf galaxies whose mergers made the disk about 10 Gyr ago (ApJ 566, 245).

The authors of a number of interpretations of observational data explicitly embrace the "both, please" scenario, in saying (a) that no one picture can account for the outer disk of M31 (ApJ 559, L13) and the range of globular cluster populations belonging to the elliptical galaxies in the Coma cluster (ApJ 568, 174), (b) that most of the halo stars of M31 and NGC 5128 formed after the mergers that gave the galaxies essentially their present mass (AJ 122, 3065) or conversely that E and S0 galaxies made most of their stars at redshifts greater than 5 (before they were put together) but there was a second episode of accretion at $z = 1.5 - 2.0$ consisting of stuff that was also already mostly stars or became so very quickly (ApJ 563, 629), (c) that the halo of Cen A is best fit by a description in which

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star formation and the accretion of new gas occurred simultaneously through the whole galaxy (AJ 123, 3108), while the globular clusters of most gE's seemed to have formed in two episodes, one at redshift larger than 5 in protogalactic fragments, and the second near $z = 2$ as the pieces were put together to make the galaxies we now see (MN 333, 383), and (d) just to confuse the issue, that the globular clusters of the Milky Way could also come from two formation episodes (ApJ 559, L113, though the author makes it sound as if both of these were part of a monolithic process) or from a single episode, also in top-down galaxy (AJ 122, 3136). An interesting variant, which you might call "all of the above" attributes the Lyman-alpha clouds to gas blown out of the first generation of galaxies which then merge to produce second generation galaxies (Astrofisica 43, 1). Whatever happened, some of it happened very early. We alluded above (Sect. 4) to the existence of some quasi-stellar objects at redshifts near 6, and there is at least one fully assembled X-ray cluster, with hot gas and galaxies containing old stars, at $z = 1.1$ (AJ 123, 619).

No, it does not at the moment seem possible to tell a single, coherent story which encompasses all of the conclusions just described, and there may never really be such a story. A theoretical colleague has described modern cosmology as consisting of two pieces: the purely mathematical exploration of general relativity, alternatives to it, and their consequences, which he likened to chess, and the physical exploration of the formation and evolution of real structures in the universe, which he likened to mud wrestling. This subject is in the mudwrestling phase.

10. Sound Bites

There are, of course, many, many other areas of research pertaining to galaxies and the universe within which important things have happened in the past triennium. Here is a handful, presented in the form of a question and a potential (but typically not fully agreed-upon) answer. The topics are treated in this cursory fashion partly because we suspect that the definitive answer is not yet in and partly for sheer lack of space.

Do other galaxies have high velocity clouds (that is, infalling clouds of hydrogen with or without heavy elements that might be the "return current" of galactic fountains or continuing accretion of virgin intergalactic material)? There is a good deal of evidence for the hot, outgoing part in chimneys and fountains (A&A 360, 24, A&AS 145, 83, ApJ 524, 98, A&A 359, 433, MN 309, 395, A&A 358, 812). But HI with anomalous velocities relative to the nearest galaxy is distinctly rare (ApJ 530, L61), though not completely unknown (AJ 123, 3124 on NGC 2403). Best available answer, "maybe".

Is that very bright high redshift source an active galaxy or a star burst? The answer seems to be that, in very many cases, it is both, and there is not necessarily any evolutionary relationship between the two, though both might quite reasonably be expected to result from mergers making fresh gas available (PASP 113, 1025, sect. 11.4, and most of the 30 or more relevant papers published in the last 10 months, e.g. ApJ 572, 105, PASP 114, 593, A&A 382, 828, MN 327, 1183). Indeed, the same can be said about a good many low-redshift sources, for which the components can be separated out more clearly (AJ 123, 1922 on N 4410A, ApJ 564, 688 on Cen A, MN 333, 707 on NGC 6240). In other words the answer seems to be "both, please", and perhaps we should have expected this all along (ApJ 573, L81).

What is the origin of large scale (cosmic) magnetic fields? There exist coherent fields on scales at least as large as that of clusters of galaxies (e.g. ApJ 567, 202). The two main answers to where they came from have historically been "primordial" fields and "dynamo" field. Another way of saying this is that the choices are starting with the very largest scales and something associated with the early universe like domain walls (PRL 85, 5268) or lepton asymmetries (PRL 88, 011301) or starting with much smaller scales, where there are currents and fields of the sort one might think of finding in a laboratory, associated, for instance with AGNs and their radio lobes (ApJ 556, 619, Nat. 415, 31, ApJ 560, 178). Other support for the primordial picture is found in A&A 378, 777 and PRL 87, 251302.

A still smaller scale origin is found in ApJ 563, L15 which attributes the first field input to gamma ray bursters at large redshift.

What has become of the missing satellite galaxies? What, you didn't know you had lost any? Well, standard models of the formation of large scale structures (galaxies and clusters) say that there should be nearly a thousand little things for every big thing. This is clearly not what we see. The Local Group has at most three dozen dwarf galaxies to accompany its two or three large ones, and recent searches for additional dwarfs have found nothing (ApJS 141, 123). Even in rich clusters, though dwarf galaxies again greatly outnumber giants, the ratio is not the predicted one (MN 333, 423 and probably 25 other papers in the triennium, of which this just happens to be the last published). There are nearly 1000 (well, 300+ anyhow) globular clusters in the Local Group. Perhaps they are the remnant cores of the missing 1000, the rest having been torn up to make the halo we now see (Nat. 402, 53, ApJ 548, 33). Alternatively, reionization might have prevented gas from flowing into the smaller halos that should have turned into these dwarf galaxies (MN 333, 156), so that they can be found only by their dynamical or lensing effects on their surroundings.

What sorts of galaxies host gamma ray bursters? This is an unfair question, since only the long-duration subset of the GRBs can yet be associated with hosts (or any other sort of counterpart at any wavelength). The answer, however, is "star-forming galaxies" (PASP 113, 1025 sect. 9.2, PASP 114, 475, sect. 9.2, A&A 388, 425, AJ 123, 111, ApJ 566, 229, Astron. Rep. 45, 517, ApJ 565, 829, ApJ 562, 654, A&A 380, L21, ApJ 560, 652), indeed star-forming regions (ApJ 565, 174), to the extent that their numbers vs. redshift track star formation vs. redshift (sect. 8) according to ApJ 563, L123 and ApJ 561, 171. The burst of gamma rays destroys dust along the beaming direction in a fraction of a second, so that light in all wavebands can get out (ApJ 563, 597). See, however, Astron. Lett. 27, 411 for a dissenting view.

Do the constants of nature vary with cosmic time or length scale? There have been two alarms during the triennium. First is evidence from QSO absorption lines that the fine structure constant was smaller by about a part in 10^5 at redshifts of 1-3, but without any clear trend within that range (PRL 87, 1301, MN 327, 1208). Some have assumed that it must be the charge on the electron, e, which is changing (PRL 88, 031302), but this could result in a violation of the second law of thermodynamics (non-decrease of entropy) for black holes, while a change in the speed of light, c, would not have this problem (Nat. 418, 602). The second was an apparent deviation from $1/r^2$ for ordinary Newtonian gravity on a length scale of 10-30 AU from the Doppler tracking of Pioneer 10 and 11 as they leave the solar system (PRD 65, 082004, Phys. Lett. D51, 13). No such deviations have been found at small scales where particle physics somewhat expects them (PRL 86, 1418). Two measurements of the current, local value of G supposedly have uncertainties of only parts in 10^5, but they differ by parts in 10^4 (PRL 85, 2869, PRL 87, 1101) at 6.674215 and 6.67559 times whatever power of 10 is called for in your unit system. Just be glad you never learned the value past $6.67 \times$ something.

What is (or are) the dark matter? The conventional components (cf. Sect. 2) are dark baryons (brown dwarfs, old white dwarfs, and gas in phases that are difficult to see), neutrinos (hot dark matter), several possible forms of cold dark matter (neutralinos, axinos, possibly primordial black holes or assorted singularities), and, of course, dark energy or quintessence. The non-conventional components add up to many dozens. To those of PASP 113, 1025 Sect. 1.24 and PASP 114, 475, Sect. 12.5, we can add axion-photon oscillations (PRL 85, 161302), annihilating dark matter (New Astron. 6, 425), topological solitons (PRL 88, 041601) and point-like objects with their own gas halos (A&A 382, 6). There was also a good deal of enthusiasm for warm DM (ApJ 559, 516, ApJ 561, 35, ApJ 562, 593, MN 329, 813) and a new limit on primordial black holes (A&A 388, 676). The candidate of the triennium was, however, undoubtedly self-interacting dark matter. A burst of enthusiasm (PRL 84, 3760, ApJ 534, L127, PRL 84, 5258, ApJ 535, L21, ApJ 534 L134, MN 315, L29) had a tail that lasted a year or so (ApJ 568, 475, PRL 87, 141301, PRL 85, 091304) and then decayed into disagreements with the observations (ApJ 561, 61, ApJ 564, 60).

Is the standard, general relativistic cosmological picture right? This has two pieces. First, is it right in the regime from, say, big bang nucleosynthesis onward? Some alternatives are given fairly short shrift in Sect. 2. Second, is it the whole story? The answer to this is surely no. Inflation has been around too long to be credited to this triennium (but see Sci. 295, 2224 for an update). Introductions to some of the still more exotic ideas can be found in Sci. 296, 1422 and 1427 (extra dimensions), PRL 89, 061302, PRL 87, 231301 and ApJ 565, 661 (brane worlds) and Sci. 296, 639 (the ekpyrotic universe). And since we have now followed the alphabet well beyond zebra, this is clearly the place to stop.

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