UC Irvine

UC Irvine Previously Published Works

Title

Constructing the Cosmos, from Sunboats to Superclusters

Permalink

<https://escholarship.org/uc/item/27k2m1s6>

Author

Trimble, Virginia

Publication Date

2005

DOI

10.1007/1-4020-3748-1_2

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at

<https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

CONSTRUCTING THE COSMOS, FROM SUNBOATS TO SUPERCLUSTERS

Virginia Trimble

*Department of Physics and Astronomy, University of Maryland,
College Park, MD 20742, USA*

vtrimble@uci.edu

Abstract Our current understanding of the nature and origins of the large scale structure of the Universe has arisen from the very long sequence of earlier understanding, with size and time scales and complexity increasing more or less monotonically. This history is explored beginning with ideas from pre-literate societies and ending with some fine tuning of the current “consensus cosmology”.

Introduction

Three coherent themes appear as we examine changing notions of what the world as a whole is like: Expanding horizons, Hierarchical levels of structure, and Increasing mediocrity.

Expanding horizons: To most pre-literate and immediately postliterate societies (not all), the world was the Earth and it was a size that could be circumnavigated by humans in a lifetime and by a god in a day. Examples include Apollo and his chariot, the traditional Indian structure of tortoises supported by elephants supported by tortoises (etc.), and the ancient Egyptian earth god Geb overarched by the sky goddess Nut, supported by the air god Shu. Around this, the sun god Ra sailed once a day, changing between his day and night-boats at the horizon, thus accounting for the slight slowing of the apparent motion of the sun at the horizons, which we now attribute to differential refraction in the atmosphere.

In contrast, the modern universe is at least 10^{10} LY (Light Year) in extent by direct observation, arguably at least 10^{15} LY in extent from the absence of gradients, and (because once inflation gets started it is not so very anxious to stop) could be $10^{10^{100}}$ LY in extent, the size at which replications occur, so somewhere else you are also reading this paper, and yet somewhere else I am writing it. Statements about recent cosmological ideas that are not otherwise credited here come from a meeting “Concordant Cosmology and Beyond” held

in Cambridge, UK during the first week of the Erice summer school. At least one respectable scientist thought each was likely to be correct, at least for the 30 minute duration of his talk. Yes, the Cambridge meeting, like the summer school, had only one senior woman speaker.

Time scales have expanded correspondingly. Most mythical worlds (that of Genesis, of the Australian aborigines and the North American Indians, though not that of the Asian Indians) had endured from 100 to 1000 generations since creation by some higher authority, with the expected future duration comparable. In contrast, the time since our universe was very different (hot and dense) is known to be 13.7 Gyr with considerable precision (Bennett et al. 2003). Its future life expectancy could be infinite and is, at minimum, at least 50 Gyr to a big crunch (if the negative pressure stuff decays away) or a big rip (if the negative pressure stuff takes over completely). Some brane world cosmologies and others (discussed by P. Steinhardt in Cambridge) are cyclic, with finite time between bangs but infinite total duration.

Hierarchical levels: Early, earth-centered worlds were widely held to be unique (Trimble 2004 for details and references). A heliocentric solar system soon suggested the possibility of other planetary systems orbiting other stars. That stars are genuinely clustered in some cases (and in bound pairs in others) was shown statistically by John Michell in 1767. Then came other galaxies like the Milky Way and the first grouping of galaxies, the Local Group (these both from Edwin Hubble in 1923-24 and 1936 respectively). All astronomers active in the field now recognize that galaxies are clustered and the clusters, often to be found in sheet-like and filamentary superclusters around extended voids, although until rather recently there were defenders of the idea that the distribution of galaxies in space is really quite homogeneous and the structures we see are due to differential interstellar absorption. In between, Fritz Zwicky (1961-68) long held the view that there were clusters but no superclusters, and from this deduced that the range of the gravitational force was not much more than 10 Mpc, and the mass of the graviton was 10^{-63} g.

Are there levels of structure and organization still larger than the 100 - 200 Mpc aggregates seen in modern extensive surveys of galaxy redshifts? DeVaucouleurs (1970) felt strongly that there should be, on the grounds that it would be very strange that he should be writing just as the largest structures had been mapped and just as estimates of the age of the universe stopped increasing with time. Strange, but, it seems, true, and the preponderance of current data strongly suggest that supercluster structure joins smoothly onto fluctuations in the X-ray background and those, in turn, join onto the very small fluctuations of the cosmic microwave background (Jones et al. 2004).

Decreasing centrality; increasing mediocrity: It gradually became clear over the centuries that we are at the center of neither the solar system nor the Milky Way Galaxy. Neither we, nor anyone else, can be at the center of

a general relativistic universe, whether finite or infinite (as noted by Digges before 1600). In addition, there are enormous numbers of stars very much like the Sun and enormous numbers of galaxies very much like the Milky Way. At least 5-10% of sun-like stars have one or more planets, and it could be all of them have planets, though current search techniques can reveal only massive (Jupiter-like) planets in relatively short period orbits (Butler et al. 2003 and references therein). Are there other universes, in the sense of other four (or more) dimensional space-times with which we cannot communicate, even in principle? That there are is one of the implications of selfreproducing, eternal, chaotic inflation (Linde 1996) and of some of the others of the roughly 125 "flavors" of inflation (from anisotropic brane to TeV-scale hybrid) compiled by Paul Shellard. Uniqueness is also possible.

To what extent are these three themes played out? Additional levels seem to have been exhausted, i.e. we see the largest structures in the observable universe. The temporal and spatial extent of that universe hovers between absolutely enormous and infinite, and no observation on the near horizon can settle the issue. The two are, however, conceptually different. If merely "enormous", then a non-trivial portion is sampled by existing and future data; if "infinite" then our sample will always be a set of measure zero of the total, and so perhaps not at all representative. The same would be true if we are one of an infinite number of (finite) universes, though not if there are "only" the 104 of the Calabi-Yau manifolds mentioned by P. Steinhardt at Cambridge. As for mediocrity, no very earth-like planets have yet been found nor can they be with existing techniques employed from the ground (Trimble 2004 and other papers in the volume), but we know in principle what is required and how to recognize another Earth if it should turn up. A spectrum with the red absorption edge produced by chlorophyll (seen in integrated earth light reflected from the moon) is perhaps more than we can expect, or perhaps not. Observations that might reveal the existence of other universes are rather difficult to come by, but it is not unreasonable to look for signs of the kinds of inflation that lead us to expect them.

Despite these fairly coherent three themes, it will turn out not to be possible to tell the story of the discovery of the large scale structure and evolution of the cosmos in a single, linear tale, because, to take only one example, Charlier is looking for hierarchical clustering of galaxies and Lundmark is measuring the distances to a few nearby ones by the same time (1910-23) that Shapley, van Maanen, and others are denying the very existence of such galaxies.

OUTWARD STEPS

The following are brief verbal descriptions of major stages from earthsized and earth-centered to really big and centerless. Most can also be presented as

images, and were, taken from standard texts (Jaki 1972, Whitney 1971, Struve and Zeberg 1967, Berendzen et al. 1976, Peebles 1993, Harrison 2000).

1. *The size and shape of the Earth.* Arguments for a spherical Earth were known to the Greeks, and its size measured by Eratosthenes (c. 200 BCE) by the classic method of examining shadow lengths at noon at two different latitudes whose linear separation was known. The accuracy of his answer depends on the somewhat uncertain length of the Roman stadium. Sphericity was sometimes forgotten, for instance in the drawings around 1150 CE by Hildegaard of Bingen (who also put hail and lightning further from the Earth than the inner planets and fixed stars). The overall structure was pineapple shaped. The earth was re-rounded by Thomas Aquinas in his circa 1250 CE synthesis of Greek philosophy (mostly Aristotle) and medieval church doctrine, and the round shape carried over into Protestantism by Martin Luther and others.

2. *The distance to the moon.* Hipparchus in 130 BCE or thereabouts used the curve of the terrestrial shadow across the moon during eclipses to estimate this in units of earth radii and got roughly the right answer. A geometrical method for determining the ratio of sun distance to moon distance failed, because the lunar orbit is not a circle.

3. *Non-centrality of the Earth.* Aristarchus and other Greeks considered this possibility and were aware that stellar parallax was a definitive test. They couldn't see it and so mostly opted for earth-centered. Copernicus, publishing almost post-humously in 1543, chose the sun as a more suitable center, though the absence of parallax distressed potential followers like Tycho (who invented his own compromise system in the late 1500s). Observational confirmation of "eppur se muovere" came only in 1729 with the measurement of aberration of starlight by James Bradley, though by then the scholarly community had long since been converted by the moons of Jupiter, the phases of Venus, and much else.

4. *The orb of star.* Copernicus put all his stars in a thin shell outside the orbit of Saturn, and not far outside. An infinite distribution was favored by Nicholas of Cusa (1450), Thomas Digges (1576), Giordano Bruno (before 1600), and Rene Descartes (1636). Reversion to a finite orb came from Kepler (1620) and Newton (1660), who, however, later considered an infinite distribution and worried about the gravitational equivalent of Olbers' Paradox. He expected Divine providence to take care of the stability of the total system, perhaps by occasionally sacrificing small portions of it to collapse. William Gilbert's 1603 stellar distribution was again declared infinite in his text, though drawn as finite (presumably owing to the high cost of 17th century paper and parchment). In addition, his stars were not all the same intrinsic brightness, as indeed real stars are not. Descartes's infinite universe was tessellated into vortices with squared-off corners, each dominated by a central star and with the potential for formation of planetary systems in the churning vortices. Otto von Guenicke

(discoverer of terrestrial vacuums, with the help of an evacuated iron sphere and two horses) returned again to a finite starry cosmos surrounded by an infinite void.

5. *The shape of the Milky Way.* That white (milky!) band was obviously known to the Greeks, and its resolution into stars was achieved, at the latest, in 1609 by Galileo. Yet it is not until 1734 that Swedenborg provided a drawing with the stars other than spherically or uniformly distributed. He had in mind a sort of magnetic dipole shape (inspired by the earth's field, recognized by Gilbert in 1600) and envisioned an infinite number of other such systems in the universe. A later (1750) drawing by Thomas Wright of Durham is most often reproduced as the first version of the Milky Way as a disk. One version of the drawing looks quite modern (his edge-on galaxy), while the other (the galaxy face on) has sort of an eye-of-god appearance. In either case, he supposed there to be an infinite number of such systems. William Herschel, with a way of estimating stellar distances, was able to be somewhat quantitative about the axis ratio of the disk, about four to one (not actually as extreme as the truth), and also recorded the Cygnus rift as an uneven edge to the disk, which we now attribute to interstellar absorption of starlight. His best known drawing dates from 1785.

6. *The distances to the stars.* If the stars are suns, they must be enormously further away. John Michell, the first to be quantitative about this said millions of times in 1767. "At least," we would now say. William Herschel refined Michell's method to his "star gauging" and concluded that the disk was a kilolight-year or so across. Firm numbers for stellar distances came only with the first measurements of parallax, almost simultaneously in 1838 by Bessel (of the functions), Struve (the middle one of a dynasty), and Henderson (working from South Africa and so able to choose Alpha Centauri for his campaign).

7. *Position of the Milky Way in the scheme of things.* From William Herschel to Jacobus Kapteyn (1920), nearly every authority had a Milky Way of stars with the sun at or very near its center, sandwiched in a finite "realm of the nebulae". William Huggins, who showed that many nebulae are truly diffuse gas and not unresolved star clusters, concurred around 1860, as did Harlow Shapley in 1920. The Third Earl of Rosse, with his homemade telescope (well, they all were in those days) was the first to resolve the spiral arms of a few of these nebulae, beginning with M51. Doubters seem to have been few, though Simon Newcomb (first president of the American Astronomical Society), who otherwise has rather bad press, asked rhetorically in 1901 whether we might be victims of some fallacy (like that afflicting Ptolemy) in thinking ourselves at the center of the Milky Way. He also asked some very modern-sounding questions about the extent and duration of the universe, the form and extent of the stars of large proper motion, which would have passed through Herschel's Milky Way in only a million years (and sorting that one out required

both an understanding of star formation and the discovery of dark matter!). Cornelius Easton in 1900 drew a perfectly charming spiral Milky Way with the sun solemnly at the center of all the circles, but the center of the spiral pattern far off to one side toward Cygnus. Several contemporaneous drawings (Eddington; Alfred Russel Wallace) have a heliocentric galaxy with a ring of stars outside the main ellipsoid. This is probably Gould's belt.

8. *Non-centrality of the Sun.* The Curtis-Shapley debate (Curtis 1921, Shapley 1921) centered on this and on the distance scale of the galaxy. Curtis said small, sun-centered while Shapley said big, with the sun something like 20 kpc from the center, based on his distance scale for globular clusters, derived in turn from the apparent brightness of the RR Lyrae stars in them. Shapley was pretty much the winner on this one, and he has been compared with Copernicus for moving us away from the center.

9. *Some nebulae are actually other galaxies, island universes, and such.* Herschel held at various times to both viewpoints – nebula independent, or nebulae part of the Milky Way. Michell in his 1767 paper had already said that if those fuzzy things were as big as the Milky Way, then the brightest stars in them should appear at $V=13.8$ (too faint for him to see). Herschel, Curtis, and Lundmark were "external galaxy people" up to about 1923. Shapley, van Maanen, and others were "everything inside" people. The issue was definitely settled by Edwin P. Hubble in 1923-24, when he found and measured light curves for Cepheid variables in NGC 6822, M31, and, in due course, other galaxies.

Recognition of the rotation of the Milky Way by Bertil Lindblad and Jan Oort (who is generally assigned the lion's share of the credit) belongs also to the mid 1920s.

10. *Existence of interstellar dust and absorption.* Somewhat confusingly, the stuff that was responsible for the misconceptions by Herschel, Kapteyn, and all, was not recognized until after the distance scale and other galaxy issues had been settled. The possibility of interstellar obscuration had been debated for decades; its existence was settled by Trumpler (1930) who noticed that distant star clusters looked fainter than they should if all were about the same size and light fell off only as $1/R^2$. A peacemaker, it seems, he drew a Milky Way centered where Shapley's globular clusters said it should be, but with a "Kapteyn universe" within the dusty disk, centered at the sun, and cut off where obscuration reached a few magnitudes at a couple of kpc away from us. It took some years for the community to re-evaluate the distance scales chosen by Hubble and Shapley in light of this obscuration, and the eventual effect was to make the galaxy rather smaller (8.5 vs. 20 kpc to the center) and other galaxies more distant (by a factor 7-10) than the pioneers had found.

11. *Nebulae are paired and clustered.* Non-randomness of fuzzy things in the sky was remarked upon by both the Herschels, and anyone with ac-

cess to Messier's catalog could have seen it. His catalog of things that were not comets (his only real interest) contained 107 fuzzy objects (though only 6 were known to Halley in 1715 and the Herschels took the numbers about 103) and if you color code them for spirals, ellipticals, and star clusters, at least the Virgo and Leo clusters pop out at you and perhaps a couple of others. But they were not color-coded for Messier, and spiral arms belong to the 1850s, not the 1750s when he began collecting his non-comets. If you plot them all, the most conspicuous grouping is around Sagittarius and consists of globular clusters near the center of the Milky Way. After the general recognition of external galaxies, the existence of physical pairs was pointed out by Lundmark in 1932 (using the same statistical argument that John Michell had used to demonstrate pairing and clustering of stars; it is about the same as the one to figure out how many people you need in a room for two to be likely to have the same birthday). Lundmark's student Holmberg catalogued a number of pairs the year after Hubble (1936) pointed out that we live in a crowded region, which he dubbed the Local Group (the first group or cluster to be recognized). Hubble maintained that clusters, though the Local Group, Virgo, and Coma certainly existed, were rather rare, while Shapley and Bart Bok, also in the 1930s, claimed that most galaxies were clustered. The issue was resolved, again statistically, by J. Neyman (a well known statistician) and his student Elizabeth Scott at Berkeley in 1953. Clustering is the norm. Carl Charlier, in 1908 and 1920, was the last person to look at this issue before the nature of the nebulae had definitely been settled. He recognized clustering and super-clustering and was a firm advocate of a fractal universe (as a solution to Olbers paradox among other virtues).

12. *The redshift-distance relation.* Lundmark in 1925 and H.P. Robertson and Georges Lemaitre in 1926-28 had attempted to correlate the galactic wavelength displacement measured by Vesto Melvin Slipher (at Lowell Observatory) with estimates of galactic distances but were not taken very seriously. Lemaitre's value for what we now call the Hubble constant would have been about 600 km/sec/Mpc. Edwin P. Hubble (again) settled the issue for most astronomers with his 1929 velocity distance relation. The velocities were still Slipher's, though Milton Humason was soon adding larger ones from the 100-inch telescope on Mt. Wilson. What Hubble did better were the distances, using variable stars, brightest single stars, and soon whole galaxies as his standard candles. Well, all right, his distances were wrong by a factor somewhere around 7 to 10, and yielded a Hubble constant (k term to him, though one doesn't suppose he really objected to the new name) of $H = 500\text{--}550$ km/sec/Mpc, with an estimated error of 10%, as Hubble constant estimated errors have been from that day to this. But, they were selfconsistent, so that the linear relationship could be seen.

13. *Higher-order clustering.* Superclusters were discernible in the 1953 analysis by J. Neyman, E.L. Scott, and C.D. Shane of the counts of galaxies carried out by Shane and Wirtanen from the Lick Observatory at that time. The Palomar Observatory Schmidt survey plates began appearing about the same time, and George Abell firmly advocated the existence of superclusters from the time of a 1961 meeting on the significance of large velocity dispersions in clusters. The existence of superclusters was equally firmly denied by Fritz Zwicky from 1936 until his death in 1974 and by V.A. Ambartsumian and his associates into the 1990s. This was never quite as clear a contradiction as it sounds. Many of Zwicky's "clusters" had substructure and were, on a modern distance scale, 40 or more Mpc across, that is, not so very different from Abell's superclusters. Are there yet larger structures in a hierarchical or fractal distribution? Swedenborg, Wright, Charlier, Lambert (up to 1920) said yes, often to avoid an Olbers' paradox. So also said Gerard Henri de Vaucouleurs, but evidence spanning from deep redshift surveys, to the X-ray background, to the microwave background says **NO**.

14. *Expansion of the extragalactic distance scale.* H was once 500; now it is 55-75 km/sec/Mpc (my error bars are larger than some other people's here). Step one was taken, oddly, because Baade could not resolve RR Lyrae stars in Andromeda with the then new 200-inch Palomar Mountain telescope (and David Thackeray could in the Magellanic Clouds with a 74 inch), though Mineur and Behr had got there first, before and during World War II. Additional sorting out led to 250 to 125 to 100 and below, with a prolonged period during which most calculations were done assuming 100, because it made the arithmetic easy. The use of $H = 100$ km/sec/Mpc is the modern survival of that era of good feeling. There was also a prolonged period of not-so-good feeling, during which hostile camps defended 100 and 50 (see Trimble 1996 for further details).

15. *Recognition of large scale velocity deviations from smooth Hubble flow.* These are surely to be expected if there are large density fluctuations. The first data had a great deal of scatter (Rubin et al. 1973, 1976), which led to the distrusting name "Rubin-Ford effect". Still another decade later, other groups reported comparable large scale deviations (including one associated with a not-very visible "Great Attractor"), and the Milky Way was shown, from a dipole moment in the 3K background, to be part of such a large scale flow, at about 600 km/sec (Lubin and Vilella 1986 was the first public announcement of this). Deviations from Hubble flow are now generally recognized, with the reminder that you need a distance indicator other than redshift if you are to find them.

THE UNIVERSE TODAY

Fairly definitive things can now be said about both the global properties of the universe and the merely large scale. On the global side are the values of the cosmic constants now measured by various combinations of (1) apparent brightness of distant Type Ia supernovae, (2) brightness fluctuations around the sky on various angular scales of the cosmic microwave background radiation, (3) gravitational lensing of galaxies and quasars by (other) galaxies and clusters thereof, (4) calculations of product nuclei expected from the early, hot dense universe ("Big Bang") in comparison with the amounts of these (normal hydrogen, deuterium, helium-3 and helium-4, and lithium-7) found in unprocessed gas, and (5) numbers, masses, and sizes of clusters of galaxies, often in comparison with predictions of what should have been formed by the present moment in a simulated universe with particular initial conditions. These numbers will undoubtedly continue to change slightly as more data are collected and analyzed, particularly later years of measurements by the Wilkinson Microwave Anisotropy Probe (WMAP), but, one hopes, not by more than two or three standard deviations. Table 1 is largely taken from Bennett et al (2003).

The merely large scale structure is typically described as sheets, filaments where these cross, and knots, where those cross, of larger-than-average density of galaxies, bordering under-populated (but not entirely empty) voids. The first large survey of galaxy redshifts that revealed this structure in most eyes is generally described as "the Harvard slice" (de Lapparent et al. 1986), reflecting the inability of the average astronomer to distinguish the various parts of the Center for Astrophysics in Cambridge, Massachusetts. The topology has been variously termed bubbles, foam, and sponge, this last meaning that both the high- and low-density regions connect up with others. The average void size is about 40 Mpc (Hoyle and Vogeley 2002), and the galaxies inside them tend to be rather puny things (Mathis and White 2002).

The most extensive picture of how the galaxies are currently distributed in three dimensions and how this has changed in the recent past will eventually come from the Sloan Digital Sky Survey (SDSS) which has already revealed some evolution, (Dodelson et al. 2002). Interim pictures, particularly nice because they show the filament/sheet/void pattern repeating many times, belong to the 2dF (Two-degree field) redshift survey (Peacock et al. 2001), the Southern Sky Redshift Survey (da Costa et al. 1998), and the Las Campanas redshift survey (Shectman et al. 1996). There are corresponding fluctuations of velocities of galaxies around smooth Hubble flow, at worst "not inconsistent" with the density fluctuations (Zehavi et al. 2002).

Table 1. Cosmological parameters

Parameter	Value
Hubble's Constant	$H_0 = 71 \pm 4 \text{ km/sec/Mpc}$
Critical (closure density)	$\rho_c = 9.45 \times 10^{-30} \text{ g/cm}^3$ (or energy equivalent)
Total Density	$\Omega = 1.02 \pm 0.02$ (in units of critical density)
Age of the Universe	$t = 13.7 \pm 0.2 \text{ Gyr}$
Baryon Density	$\Omega_b = 0.044 \pm 0.004$ (of which 0.01 is critical density)
Matter in all forms	$\Omega_m = 0.27 \pm 0.04$ (of which nonbaryonic $\simeq 0.23$)
Dark energy	$\Omega_x = 0.73 \pm 0.04$ (with equation of state parameter w less than ~ 0.78)
Neutrino density	$\Omega_n = 0.01(0.006 \text{ for likely neutrino}$ masses, 3 light flavors)
Temperature of CMB	$T = 2.725 \text{ K}$
Photon density	$N_\gamma = 410 \text{ } \gamma/\text{cm}^3$
Baryon-photon ratio	$\eta = 6.1 \times 10^{-10}$
Initial fluctuation spectrum	$n = 0.833 \pm 0.086$ at 0.05 Mpc^{-1} , steepening to 1.03 ± 0.04 at 0.002 Mpc^{-1} (it is not impossible that $n = 1$ on all scales is still correct)
Redshift of decoupling	$z = 1089 \pm 1$ (but thickness $\Delta z \simeq 200$)
Age at decoupling	$t_d = 380 \text{ kyr}$, with thickness of 120 kyr
Redshift of matter = radiation	$z = 3200 \pm 200$
Normalization of power spectrum	$\sigma_8 = 0.84 \pm 0.04$ (0.9 ± 0.1 in a later paper)
Baryon optical depth	$\tau = 0.17 \pm 0.04$ (that is, only 84.4% of the photons liberated at decoupling get through to us unscattered)

THE UNIVERSE OF THE (NOT TOO DISTANT) FUTURE

Do I expect the main items mentioned in the previous section to change significantly in my lifetime? No. Neither, of course, did Ptolemy or William Herschel, and they were right. Major scientific reorientations always take time. What are some of the things we might reasonably expect?

- Better numbers, and independent numbers from other considerations for the standard parameters, for instance W from X-ray clusters, the tilt (or not) of the primordial density spectrum, and the optical depth back to recombination from later WMAP data. Supernova work should improve the limits on the equation of state parameter, w quite soon.
- Reconciliation of some discrepant numbers, for instance W_m and s_8 whose best fits from clusters of galaxies are respectively a bit smaller and a bit larger than the consensus ones.
- Additional alternatives to inflation, with, one hopes, additional predictive power. Inflation tells us that W and n should both be unity and that the fluctuation spectrum should be Gaussian and adiabatic, but it does not tell us either how that W should be divided among the various constituents or what the amplitude of those fluctuations should be. Depending on your attitude toward anthropic considerations, it may or may not interest you to realize that a universe with W_x larger than 0.9 or so would never form galaxies and one with characteristic fluctuations $D_{T/T}$ outside the range 10^{-6} - 10^{-4} would either (at the low end) also never form galaxies or (at the high end) turn everything into big black holes.
- More details of the large scale distribution of galaxies as the full SDSS data set becomes available. Already it and 2dF seem to connect up the current power spectrum of density fluctuations vs. length scale very nicely with the CMB numbers.
- Reconciliation (or perhaps clearer contradictions!) of the details of structures made by Λ -CDM simulations with those in the real world. The standard problems are generally described as "missing satellites" (the expectation of more substructure in dark matter halos than we see in the luminous stuff) and "core/cusp" (the steeper rise in central density of the simulations than we see in centers of galaxies and clusters). There are perhaps some other issues, like the pair-wise velocity dispersion. All occur on length scales where feedback from what the baryons are doing must be important and has not yet been fully included in the calculations.
- Better understanding of what, when, and where the first lights in the universe were. By $z \sim 6$, there were big, metal-rich galaxies, quasars as

bright as any that came later, and enough UV photons to keep diffuse intergalactic gas more than 99.9% ionized. It is generally advertised that stars (probably very massive and certainly very metal poor stars) began the re-ionization process and the QSOs (quasi-stellar objects) later maintained it, but "more work is needed". In one particular realization of a universe with $W_m = 0.3$ and $W_x = 0.17$ (carried out by Tom Abel), the very first star had a mass near 300 $M_\odot$, formed in a halo of about 106 $M_\odot$, and left as a remnant a black hole of 50-80 $M_\odot$, which might then have become a seed for an active galactic nucleus. It happened at $z = 58$!

ACKNOWLEDGEMENTS

Colleagues from Abell to Zwicky have contributed to both communal and my personal understanding of the construction of the cosmos, but a special thank you to Patricia Henning for a most unexpected introduction to the warmer side of Simon Newcomb.

References

- Abell, G.O., 1961, *AJ* 66, 607
 Bennett, C.L. et al., 2003, *ApJS* 148, 1
 Berendzen, R. et al, *Man Discovers the Galaxies*, (NY; Science History Publications)
 Butler, R.P. et al., 2003, *ApJ* 582, 455
 Curtis, H.D., 1921, *Bull. Natl. Res. Council* 2, 194
 da Costa, L.N., et al., 1998, *MNRAS* 299, 425
 de Lapparent, V., Geller, M.J. and Huchra, J.P., 1986, *ApJ* 302, 1.
 de Vaucouleurs, G., 1970, *Science* 167, 136
 Dodelson, S. et al., 2002, *ApJ* 572, 140
 Harrison, E.R., 2000, *Cosmology*, 2nd Edition, Cambridge University Press
 Hoyle, F. and Vogeley, M.S., 2002, *ApJ* 566, 641
 Hubble, E.P., 1936, *The Realm of the Nebulae*, Yale University Press
 Jaki, S., 1972, *The Milky Way*, NY; Science History Publications
 Jones, B.J.T., Martinex, V., Saar, E., and Trimble, V., 2004, *Rev. Mod. Phys.* (in press)
 Linde, A, 1996, in B. Zuckerman and M.A. Malkan (eds.), *The Origin and Evolution of the Universe* (Jones and Bartlett) p. 127
 Lubin, P. and Vilella, T.N., 1985, in B. Madore and R.B. Tully (eds.), *Galaxy Distances and Deviations from Universal Expansion* (Reidel) p. 169
 Mathis, H. and White, S.D.M., 2003, *MNRAS* 337, 1193
 Michell, J., 1767, *Phil. Trans. Roy. Soc.* 57, 234
 Newcomb, S., 1906, *Sidelights on Astronomy and Kindred Fields of Popular Sciences*, NY (Harper)
 Neyman, J., Scott, E.L., and Shane, C.D., 1953, *ApJ* 117, 92
 Peacock, J.A. et al., 2001, *Nature* 410, 169
 Peebles, P.J.E., 1993, *Principles of Physical Cosmology*, Princeton University Press
 Rubin, V.C. et al., 1973, *ApJ* 181, L111 & 1976, *AJ* 81, 769
 Shapley, H., 1921, *Bull. Natl. Res. Council* 2, 171
 Shectman, S.A. et al., 1996, *ApJ* 470, 172
 Struve, O. and Zeberg, V., 1967, *Astronomy of the 20th Century*, NY: Macmillain

- Trimble, V., 1996, PASP 108, 107 & 2004, in S.S. Holt and D. Deming (eds.) *The Search for Other Worlds*, AIP Conf. Proc. 713, p. 3
—, 2004, *Bull. Astron. Soc. India*, (in press)
- Trumpler, R.S., 1930, *Lick Obs. Bull.* 14, 154 Whitney, C.A., 1971, *The Discovery of Our Galaxy*, NY: Knopf
- Zehavi, I. et al., 2002, *ApJ* 571, 172
- Zwicky, F. et al., 1961-1968, *Catalog of Galaxies and Clusters of Galaxies* (in six volumes), California Inst. of Technology