Session III

Local Structure

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Emergent Structure: the First Two Centuries of the First Two Eons

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Abstract. "Early" maps of the cosmos included the 26th dynasty air god Shu supporting the sky goddess Nut above the earth god Geb, Descartes' Voronoi tesselation, William Herschel's star gauging, and Carl Charlier's 1922 plot of the nebulae in NGC, which he intended as observational support for the fractal nature of large scale cosmic structure (about which he was probably wrong, though right about there being more than one level of clustering). Because Shapley, van Maanen, and others were still denying the very existence of external galaxies at the same time that Lundmark and Opik were measuring their distances and masses and Charlier plotting hierarchies, the story of the discovery of very large scale structure (and streaming) in the universe cannot be told in perfectly linear fashion. There are, however, half a dozen or so discrete phases that can be recognized and three underlying themes, (1) expanding horizons, (2) additional levels of structure, and (3) increasing mediocrity of our vantage point.

1. Historiographic Introduction

Not all cultures look at information the same way. The Babylonians stored most of their astronomy in complex arithmetic calculations, while the Greeks concentrated on geometric images. Similarly, serious historians of astronomy and other sciences do not typically follow the same path as the scientists themselves do in looking at the precursors of current knowledge. The approach taken here is relentlessly that of the modern scientist: who did what, when, and does it agree with what we now think about the subject? And the presentation was essentially a visual one, with something like 50 images of cosmologies, world pictures, and sky plots from ancient to modern. The sources of those images are cited in Trimble (2003), and neither space nor copyright permits them to be reproduced here.

Not all the images were entirely authentic. Shu standing on the recumbent Geb and holding up Nut (with a distinctly disrespectful touch) comes from an authentic, but very late, Egyptian tomb painting. The "turtles all the way down" concept, typically blamed on Indians of the first millennium BCE is always represented by a modern drawing (with the earth as the back of a tortoise, swimming in bowl, held up by an elephant, standing on a tortoise....), and the only drawing I have ever seen of the Chinese Pan-ku separating the heavens and earth by growing in between them was one I made myself. This situation improves for times when actual books and scientific papers (papyruses, tablets,

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parchments) were produced, have survived, and can be rotagravured into secondary sources and xerocopied onto overheads.

Of the three themes mentioned in the abstract, the playing out of the first is probably complete, with horizons having expanded from the distance a human being could travel in a lifetime and a God in a day (think of Apollo's chariot and Ra's boat) to a very probably infinite universe. The trend toward additional hierarchical levels of structure has arguably ended with the largest structures now found having scales of a few hundred Mpc (unless you care to think of multiverses with different values of the fundamental constants and so forth). The increase of mediocrity and non-centrality of our location is still in progress, with the multiplicity of suns and galaxies and planetary systems guaranteed, but not that of earth-like planets, and the issue of multiple universes still open.

2. The Medieval Rediscovery of Greek Astronomy

Artistarchus entertained the idea of a sun-centered system, but the majority voted with Ptolemy and Aristotle in favor of geocentricity. The pictures one normally encounters in introductory text books of Ptolemaic cosmology were not drawn by Ptolemy but by authors of the 15th and 16th centuries. The pictures are relentlessly circular, reflecting the Aquinian synthesis of rediscovered Greek learning with Church doctrine of his period (c. 1250). A century earlier, Hildegaard of Bingen had drawn a charming flat earth surrounded by a pineapple-shaped cosmos, but the Greek discovery of relative distances (based mostly on speeds of motion through the sky) had been lost; her inner planets lie among the fixed stars, with the sun beyond amongst the hail and lightning, and the outer planets beyond on the stem of the pineapple. Luther's (1534) world also looks flat (complete with "waters beneath"), but is made of concentric spheres or circles with a divine primum mobili outside. Readers of Greek by then knew fair numbers for the size of the earth (Eratosthenes) and the distance to the moon in earth radii (Hipparchus). Everything else was thought to be further away, but not enormously further (based on an erroneous argument concerning the phases of the moon), and the fixed stars lived on a single spherical shell.

3. Plurality of Worlds

Copernicus, publishing almost posthumously in 1543, notoriously put the sun at the center, but left the relative distances unchanged and the stars on a shell. The idea of an infinite number of stars, filling infinite space, and each (or many) with their own families of inhabited planets can be found in the writings of Nicholas of Cusa (1450), Thomas Digges (1576), Giordano Bruno (before 1600), and Rene Descartes (1636). Descartes spaced his stars and their systems with vortices (tied to how planets form) that fill space in a way that looks remarkably like a two-dimensional Voronoi tesselation. The posthumous (1603) world of William Gilbert not only had infinite space and an infinite number of stars, but the stars were clearly of different intrinsic sizes and brightnesses, a point not fully appreciated by others for a couple of centuries. For these people, the issues of "horizon size" and "mediocrity" were already settled. Not all had views on hierarchies, which for several centuries tended to get tangled with Olbers paradox, rather than being regarded as something that might be settled by data. Harrison (1987) has treated this so well that there is no need to discuss it here.

The famous names of the period rode both horses at various times. Kepler considered the possibility of an endless universe, in which the sun would be an undistinguished star, but at the end settled on a bounded universe with a thin sphere (or spherical shell) of fixed stars. He also held by the Greek relatively short distances to sun, planets, and stars, getting numbers for them that satisfied his $P^2 = a^3$ law by nesting the platonic solids between spheres. Newton, contrarily, began with a finite stellar distribution, but went on to consider an infinite one. He worried about the gravitational equivalent of Olbers paradox in this context and concluded that divine providence might intervene from time to time to keep things from running amok. The less famous Otto von Guericke can be said to have discovered the vacuum, by hitching horses to the two halves of an evacuated sphere and finding that they could not pull the halves apart. Not surprisingly, his 1672 universe had an infinite vacuum surrounding a finite starry cosmos, which nevertheless contained a great many stars of different sizes and brightnesses.

4. The Shape of the Milky Way and Distances to the Stars

Although Galileo's telescope had shown the Milky Way to consist (mostly) of faint stars, it was more than a century before anyone drew the "coelum stellatum" as anything but isotropic. The first was Emanuel Swedenborg in 1734, who, drawing an analogy with Gilbert's magnetic dipole earth, produced an electric coil, or perhaps disk, of electrical current with curved field lines (not spiral arms, which had not yet been seen anywhere). Better known, and widely reproduced, is the 1750 disk of Thomas Wright of Durham. Other views of his cosmos look much more like Eyes of God filling an infinite universe. He and Swedenborg were both definitely pluralists!

Quantitative evidence for a disk configuration and something of its size came from the 1785 "star gaging" of William Herschel. He took all stars to be the same brightness as the sun, ignored the possibility of light being attenuated in any way other than $1/r^2$, and so put us near the center of a ragged (but sharp edged) disk with axial ratio 4:1 and total extent about 1000 light years. The idea that the distances to the stars could be estimated from their apparent brightnesses (and one has to be rather clever even to measure these relative to the sun) had earlier been explored by John Michell in 1767, at long last making clear why neither the Greeks nor Tycho had been able to detect heliocentric parallax, and making clear just how difficult this was going to be. About 15 years later, Michell also persuaded himself that there must be real, bound stellar pairs of different intrinsic brightness, because there were so many close pairs on the sky. He persuaded no one else, and Herschel set out to look for parallax by cataloging these pairs (on the assumption that the fainter must be more distant) for relative position measurements through the year.

Instead, parallax had to be found by the much more difficult absolute measurements of position and their annual variation, as was done successfully more or less simultaneously around 1838 by Bessel, Struve, and Henderson. We were thereafter at the center of a disk-shaped Galaxy about 1000 pc in radius (and so flatter than Herschel' s configuration). We remained so through the work of Simon Newcomb (1870-1900 roughly), who spoke of the region of stars and the region of nebulae on either side of it, whether infinite or finite being left undecided. Newcomb (who has had rather bad press over the years, connected with his dislike for spectroscopy as a part of astronomy) nevertheless asked a number of prescient questions toward the end of his life, including whether our apparently centrality might be the result of some misconception, like that of Ptolemy. He also wondered explicitly about the finite/infinite issue for both the size of the universe and its duration and about the origin and fate of stars of large proper motion (which, in the end, required both an understanding of star formation and dark matter).

Two images of the Milky Way around 1900 look almost humorous to modern eyes. Cornelius Easton draws distorted spiral arms (next section) centered around a point toward Cygnus, half a galactic radius away from the sun, which nevertheless sits at the center of the circular Milky Way disk. And Eddington (who was not alone in this) put a ring of stars (not to be regarded as a pre-discovery of disrupted dwarf companions; it was more nearly Gould's belt) around a central, slightly ellipsoidal cluster, with us just a bit off center.

Harlow Shapley, with his Cepheid-calibrated distances to the globular clusters got us out of the center of the Galaxy between about 1918 and 1921, with last gasps from the opposition in the form of the 1920 (Heber Doust) Curtis-Shapley debate and the 1922 Kapteyn universe. But mainstream texts by Henry Norris Russell, James Jeans, and others put the center 18-20 kpc away toward Sagittarius by about 1926. Robert Trumpler, the discoverer of interstellar absorption and a peacemaker at heart, draw a galaxy with the "Kapteyn universe" off to one side of the disk (with us in the middle) and the main disk centered, with the globular clusters, far off to the right (this direction convention largely persists).

Oort's recalibration of Shapley's distance scale moved us in to about 10 kpc from the galactic center, and a drawing from 1939 by J.S. Plaskett of the Milky Way seen edge on (with thin dust disk, halo stars, and globular clusters) could just as well have been one I drew yesterday, if I could draw as well as Plaskett. By 1945, the Boks found it sufficient just to provide outlines, a circle for the top view and a sort of centrally-bulged flying saucer for the side view.

That the disk must be rotating to account for the patterns of proper motions and radial velocities we see for the stars was pointed out by Bertil Lindblad in the early 1920s. Oort is more often cited, though his 1927 paper carries the title "Observational evidence confirming Lindblad's hypothesis of a rotation for the galactic system." His sun is at R = 5.9 kpc that year, but he moved it out to 10 in 1930. "Prediscoveries" of galactic rotation can be found in the papers of Andring, Seeliger, de Sitter, J. Woltjer, Charlier, and Innes.

5. The Number and Nature of the Nebulae

The ancients knew of 21 fuzzy things in the sky (Orion, M31, the Pleiades...), some of which were lost, so that Halley mentions only six. Numbers rose rapidly

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in catalogues compiled by La Caille (42 in 1755), Messier (107 in 1784), and Wm. Herschel (about 1000 in 1785). Over the next 35 years, Herschel rode all possible combinations of horses on whether all nebulae could be resolved into stars with sufficient telescopic power and whether they were inside the Milky Way. John Michell, again ahead of his time, noted in 1767 that if the real sizes of the nebulae were comparable with the (then) 1000 or so light years of the Milky Way, their brightest stars should come in at $V = 13.8$, fainter than he could look. The modern number is about 15.6.

The 19th was, all around, a messy century for the nebulae. Herschel had drawn many, trying to arrange them into evolutionary sequences. Some are recognizably planetaries, and others bright-cored edge-on and face-on spirals, even if you don't look at the catalogue numbers. But he recorded no spiral arms, though a modern beginning observer who failed to resolve, for instance, M101 with a reflector anything like as large a Herschel's $18\frac{1}{2}''$ would surely want her money back. Resolution (in both senses) came with the $72''$ speculum reflector of Lord Rosse, whose M51 at least is instantly recognizable. The phrase "spiral nebulae" then became general, being used even for some objects we would not so describe today.

The galactic-extragalactic issue continued to be debated through the first decades of the 20th century. Curtis (at the famous debate, and earlier) put them outside, at distances of Mpc, based on novae. Opik found both an extragalactic distance and a Milky Way sized mass for M31, using novae and the rotation curve measured by Francis Pease, between 1919 and 1922. Shapley, van Maanen, and many others kept their nebulae firmly inside the galaxy right up until 1923-25, when Edwin Hubble began reporting Cepheid-type light curves for variable stars in NGC 6822, M31, and many other nebulae (the word he always preferred to use). This firmly ruled out the "solar systems in formation" hypothesis that had been the alternative interpretation of spirals.

6. Grouping, Pairing, and Clustering of Nebulae

Could Messier have "discovered" the Virgo cluster? Well, anyone with a Mollweide projection to hand can easily plot up his non-comets. If you color code with blue for spirals, red for ellipticals, and brown for everything else, Virgo, Leo, CVn, UMa, and indeed the concentration around M31 leap instantly out. Messier, of course, could not do the color coding, not because of daltonism, but because he had no reliable guide to physically different types of nebulae. Nor did he desire one; to him they were all just non-comets. And if you plot them all as black dots, the non-uniformity remains obvious, but the most obvious grouping is toward the galactic center (mostly globular clusters). There are enough nearby star clusters and such that no zone of avoidance appears.

John Herschel's 1864 General Catalogue has a couple of thousand fuzzy things, whose positions in the sky were plotted up by Proctor and Waters in 1873. They used little X's for known clusters of stars and dots for everything else. Not surprisingly, the star clusters are concentrated toward the galactic plane, and the others avoid it. This correlation of nebular frequency with galactic coordinates was, of course, one of the 19th century arguments against the existence of separate galaxies or island universes. Curtis suggested obscuration

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by a ring of dust in 1920, but it took another decade to show this is the right answer. With 20-20 hindsight, one easily recognizes some of the nearer clusters in the Proctor-Waters plot, but also the Large and Small Magnellanic Clouds, which have lots of fuzzy things in them, and a couple of what must have been "selected areas" before Kapteyn coined the term, meaning that someone had simply looked very hard in a particular part of the sky.

The last such plot was Charlier's of the nebulae in Dreyer's 1888 New General Catalogue made in 1922. Charlier was a proponent of an infinite universe and required fractal, or hierarchical, structure to avoid Olbers paradox (infinite sky brightness). He believed that he had found evidence for this in the NGC plot. Just looking, one would be hard pressed to disagree, though we now recognize that some of the structures were the imprint of galactic absorption and of the selected area effect, as well as of real non-uniform distribution of galaxies.

Then (as in the Gary Larson cartoon) a miracle happens, or rather two. The recognition of extragalactic Cepheids and the correlation of redshifts with distances, allowing spectra to be used as distance indicators. Both were, of course, the work of Edwin Powell Hubble and opened the way for quantitative studies of the three-dimensional distribution of galaxies. Thus, in 1932, Shapley was already pretty sure that the galaxies in the Shapley-Ames catalog implied a great deal of clustering.

The first quantitative discussion (of NGC and Shapley-Ames extragalactic nebulae) actually considered only positions on the sky, since redshifts were still about as rare as founding members of the IAU. Lundmark, also in 1932, used the same numerical approach that John Michell had used to establish the existence of visual binary stars (but got the arithmetic more nearly correct), and concluded that the 100 close pairs he saw were far too many for a random distribution. He then handed the topic over to his graduate student Eric Holmberg, whose 1937 thesis used radial velocity and well as positional data and thereby obtained the first set of masses for binary galaxies, as well as confirming their existence (but this is part of a different story, addressed in Symposium 220 on dark matter).

Hubble himself reported and named the Local Group in his 1936 *Realm of the Nebulae.* It initially had nine members, and, on his distance scale, the sizes and masses of the seven dwarfs were smaller than those of M31 by about the same factor as M31 was smaller and fainter than the Milky Way. He described it as a group of star clouds with small relative velocities, in a volume much smaller than the average distance between galaxies. This counts as the first second-order structure.

Hubble seems always to have remained of the opinion that clustering was rare, and that most galaxies are "field galaxies". This view lingered down to the 1960s in the minds of some (including William McCrea and George Abell) who should have known better, but spoke of individual galaxies as the basic building blocks of the universe. Even before extragalacticity had been established, astronomers including Wolf, Wirtz, and Hinks had opined that nebulae were highly clustered. Shapley said the same from 1932 onward at least, and so did Bart Bok from 1934 onward. Indeed Shapley said that Hubble's problem was that his telescopes were too big, so that he could never see more than one galaxy at a time. Shapley had left Mt Wilson and its $100''$ for Harvard in 1921, and you might be inclined to taste some sour grapes in his remark, but it was right none the less.

Clustering is in fact ubiquitous (and there may be no real field galaxies, though they still appear in the literature). For most astronomers, this was firmly established by the Shane-Wirtanen (Lick Observatory) counts of galaxies in the northern sky and the statistical analysis of these counts in 1953 by Jerzy Neyman (a distinguished statistician independent of his astronomical contributions), Elizabeth Scott (his student; and we have heard rumors), and C.D. Shane himself.

The next section belongs to the Palomar Observatory Sky Survey, but this is perhaps the place to deal with the lingering alternative to large scale structure of "differential galactic absorption." V.A. Ambartsumian (1912- 1996) put this forward in 1940, handed it on to his student T.A. Agekyan, who carried it from Armenia to Leningrad, and handed it on to B.I. Fasenko, who continued to publish papers along these lines until 1996, and seems to have brought the tradition to an end. Thus we can say that all serious modern astronomers believe in the reality of clustering of galaxies.

7. The Reality of Larger-scale Structures

The POSS yielded two catalogues of clusters of galaxies, one compiled in 1958 by George Abell, who had taken the largest fraction of plates for the survey, and one in 1960-64 by Fritz Zwicky, who had been at the forefront in agitating for Schmidt telescopes at Palomar Mountain, which made the survey possible. Both found lots of clusters, a very large fraction of which (but not 100%) are real and of about the richness and distance classes indicated in the catalogues. But they differed passionately about the distribution in space of those clusters.

Abell said he saw higher-order superclusters and, by 1961, had obtained sizes and masses that we would say (allowing for his H = 180 km/sec/Mpc and so multiplying by factors of three) were about right $-10^{17} M_\odot$ in 75 Mpc volumes. Zwicky said, with at least equal firmness, that he did not see higher order clustering (and so could estimate the mass of the graviton to be 10^{-63} grams). But there is a catch. He thought of his clusters as each occupying a standard size volume, within which there might be a good deal of substructure, as indeed we would now say that there is in many superclusters, which are still merging themselves into existence. And his cell sizes were something like 20 Mpc, so that the real difference between Abell and Zwicky (apart from 26 letters) was as much linguistic as astronomical.

Once again (this is why there are observers!) further data have resolved the issue. For the Symposium participants, the "great wall" and "stick man" (Coma supercluster) of the Harvard-Smithsonian slices, the Hydra-Centaurus grouping and Shapley concentration of the southern sky redshift survey, and so forth are all familiar sights. But, as the surveys have gone deeper (2dF) and wider (SDSS), no larger structures have appeared, and we see the same patterns over and over, confirming a view expressed more than a quarter century ago by George Field (in his article in the Kuiper compendium, actually written a good deal before its 1975 publication date) that indeed there are superclusters but you should not encourage your students to work on yet larger-scale structures.

The universe, that is, does not continue to exhibit anything like fractal structure on scales beyond a couple hundred Mpc (Jones et al. 2004, for instance); rather, the amplitudes of density fluctuations vs wavelength blend smoothly into those implied by the fluctuations in the X-ray and microwave backgrounds. Would Swedenborg, Wright, Lambert, Charlier, and all still be worried about Olbers paradox? Yes, but we need not be, since the total mass-energy density of the current universe would heat it to less than 20K even if it were all instantly, $E = mc^2$, flashed to radiation.

Although large scale structure is seen in the distribution of galaxies, intergalactic gas, QSOs, and X-ray sources, it is possible to pick sources that are very poor tracers of it. The total absence of clustering of the 3C radio sources (and the corresponding Parkes sample) from the 1950s was a source of wonderment in the 1960s. Even the 31,000 brightest 6 cm sources show little beyond holes associated with parts of the sky obliterated by sidebands of very bright sources (Gregory & Condon 1991). Indeed it has taken the recent very deep surveys like FIRST to reveal clustering of purely radio-selected samples.

One should not leave the topic of the largest scales without mentioning the work of Gerard Henri de Vaucouleurs (1918-1995). After an early career in planetary astronomy, he turned his attention first to the distribution of matter in the universe and then to its rate of expansion, evolving a fractal world view in which the 1970 (for instance) values of the Hubble constant and the average density of the universe were simply points on a line relating measured values of these to the year in which they were measured. He remarked that it would be very strange if humanity had suddenly found real ages and real sizes after centuries during which the best estimates of these had grown monotonically. Strange, perhaps, but apparently true. His local value of H, about 100 km/sec/Mpc, was supposed to go with a universe in which there were ever-larger structures of ever smaller density, so that the global value was much smaller (how small he never quite said) mimicking some of the effects of a cosmological constant. Indeed anyone plotting H *vs* t in the 1960s, starting with numbers from Lemaitre, Hubble, and Robertson, might have been forgiven for thinking that it might go through zero around 1980.

Instead, as confirmed conference goers all know, H has leveled off within some band of uncertainty, whose center and width depend on who you listen to. Among my favorite numbers are $72 \pm 8, 67 \pm 10, 53 \pm 5$, and 47 ± 6 km/sec/Mpc. Yes, these have all been published in the last few years, and so have many others, but not many outside that range.

8. Large Scale Deviations from Hubble Flow

De Vaucouleurs' intense focus on the reality of the local supercluster or metagalaxy had long-range, sweet fruit, however, for he was the informal mentor on the master's thesis of Vera Cooper Rubin. Using only the spotty archival data then available, she found some evidence for net variations in velocities around the sky that could be interpreted either as rotation of the metagalaxy (what de Vaucouleur had in mind) or, in retrospect, as a dipole due to motion of the Local Group and its surroundings relative to more distant galaxies. Twenty-five years later, a much more homogeneous and carefully-calibrated data sample, gathered by Rubin and her colleagues, revealed what was briefly called the Rubin-Ford "effect" (meaning that its reality was initially doubted). The evidence was velocity residuals around a mean Hubble relation that could be fitted approximately with a sinusoid around the sky, having an amplitude about 500 km/sec. They also plotted data on E and S0 galaxies (theirs were all ScI's) collected by Allan Sandage and found a similar pattern of residuals, which Sandage initially disowned. It is now yet another 25 years later (from which you might deduce that Vera Rubin is getting old, but you would be wrong!), and the dipole in the cosmic microwave background radiation (the first of its anisotropies to be mapped) has fully confirmed that we are moving at about 600 km/sec relative to the surface of last scattering, and in more or less the direction implied by the ScI data. The phenomenon is, therefore, called streaming (rather than "an effect") and its cause sought in the large-scale density fluctuations whose discovery has been the subject of the previous couple of sections, including perhaps a Great Attractor.

The CMB fluctuations and many other species of data can also be analyzed to extract "consensus" values of the assorted cosmological parameters, including dark matter and some of its properties. These were the subjects of very many talks at Symposia 216 and 220 and need not be addressed further here.

9. Conclusions

Our three themes of expanding horizons, increasing complexity of structures, and decreasing centrality and specialness of our vantage point have nearly played themselves out. Almost all astronomers would agree that the sun is a typical star, the Milky Way a not-very-unusual galaxy, and that planetary systems are common. The more sweeping statement that we live on an ordinary planet(*) orbiting an ordinary star, far from the center of an ordinary galaxy in an ordinary group and supercluster, in an ordinary universe(*) still, however, probably has Nobel prize opportunities at the starred points. The present author is not a candidate, though others of the Symposium participants may well be.

Acknowledgments. Yes, I knew both Abell and Zwicky and am belatedly grateful to them and very many other astronomers and physicists over the years for insights I can often no longer credit to the right person. More contemporary gratitude goes to Lister Staveley-Smith and his SOC for the invitation to participate in the Symposium and to Carrollann Simmons for turning an archaic IBM typescript into the required format.

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