RADIATIVELY-DRIVEN COSMOLOGY

IN THE CELLULAR AUTOMATON UNIVERSE

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ABSTRACT

This is an updated version of my paper "An outline of radiatively-driven cosmology" (Kurucz 2000). Here the Big Bang universe is replaced by a finite cellular automaton universe with no expansion (Kurucz 2006). The Big Bang is replaced by many little bangs spread throughout the universe that interact to produce the initial perturbations that form Population III stars, globular clusters, and galaxies, but no large-scale structure. These perturbations evolve into the universe as we now observe it. Evolution during the first billion years is controlled by radiation. Globular clusters are formed by radiatively-driven implosions, galaxies are formed by radiatively-triggered gravitational collapse of systems of globular clusters, and voids and the microwave background are formed by radiatively-driven expansion. After this period most of the strong radiation sources are exhausted and the universe relaxes into gravitational old age as we know it. To relieve the boredom we present the results of gedanken experiments (Kurucz 1992) in a traditional, linear, chronological sequence in the hope of stimulating research on the many topics considered.

Subject headings: cosmology — stars: Population III — stars: Population II — clusters: globular — galaxies: evolution

THE CELLULAR AUTOMATON UNIVERSE

I repeat here the sections from my paper on "Elementary physics in the cellular automaton universe" (Kurucz 2006) about the intitial conditions that evolved into the present day universe.

Black Holes

Black holes are easy to explain without singularities. Adding mass to a neutron star causes the neutrons to collapse into boson di-neutrons with spins anti-parallel, n + n = udd + udd $\rightarrow$ uddudd = di-n. The neutron star becomes a di-neutron star. This can be a gradual transformation, not a catastrophe. If matter is added slowly, the neutron star becomes an invisible black hole and continues to grow until the fermion nature of the quarks limits the compression.

Continuing to add mass to a di-neutron star causes the quarks within the di-neutrons to pair with spins opposed so they become di-quark bosons with 0 spin, di-n = uddudd $\rightarrow$ uu-dd-dd = di-q-di-n. The di-neutron star becomes a di-quark-di-neutron star which is a super-massive black hole.

A cellular automaton has to have a density limit to prevent overloading the "computation" in a small volume. The simplest cutoff is to make gravity repulsive at high density to automatically blow apart dense concentrations. This could be built into the cellular rules for each particle.

Antimatter

There is a missing anti-matter problem if this universe began in a Big Bang of radiation. Starting with radiation implies that all primordial particles were made by pair production as the universe cooled. If pair production does not dominate, then matter and antimatter do not have to balance.

The idea of a di-quark-di-neutron black hole suggests that our universe "started" from a collection of ultra-massive black holes statistically uniformly distributed throughout the cellular automaton. For example, the initial state might be 10^{12} to 10^{13} 10^{13}-to-10^{14}-solar-mass black holes with average separation less than a megaparsec.

At the first tick the density in the ultra-massive black holes exceded the density cutoff so gravity was repulsive. The ultra-massive black holes expanded at sub-light speed. The di-quark-di-neutrons expanded and became di-neutrons. The di-neutrons expanded and became neutrons. The neutrons expanded and became protons and electrons and anti-electron-neutrinos, and deuterons, and alpha particles, etc. The initial number of neutrons was fixed. The proton number, the electron number, and the anti-electron-neutrino number are equal. Subsequent pair production does not affect the baryon (neutron+proton) total. There is no antimatter problem. The universe is fundamentally biased toward matter.

The statistical equilibrium and the formation of nuclei led to different abundances, including heavier nuclei, and different properties than we are used to from a Big Bang prediction.

FORMATION OF PERTURBATIONS

Figure 1 shows the randomly positioned cold ultra-massive black holes that fill the universe with mean spacing less than one megaparsec. Each black hole has twelve or thirteen neighbors with which it will collide once it expands. At the first tick of the cellular automaton the particles take their first step and the black holes expand in ultra-massive supernova-like explosions. The massy particles move outward at less than the speed of light. They interact, heat, and generate photons and neutrinos that move outward at the speed of light into the emptiness of the cellular automaton. After a million years they pass photons and neutrinos coming in the opposite direction from the neighbors. The massy electrons, protons, neutrons, He, Li, Be, B, C, N, O, et cetera travel much more slowly. It takes millions of years before the massive shells collide with their neighbors.

The expanding shells lose material in the backward direction. They radiate thermally in all directions and cool. The radiation eventually, after one or two million years, reheats all the neighbors. Each expanding shell is hit by twelve or thirteen radiative precursors in sequence from its neighbors. All the background radiation is absorbed. There is no background radiation left from the initial universe.

Continuing with Figure 1, the expanding shells collide, pancake, and facet. Eventually amoeboid condensations fill the interstices with the material from twelve or thirteen successive collisions from different directions. The amoebas are filled with perturbations varying in size from few-hundred-solar-mass Population III-star-size, to one- to ten-million-solar-mass globular-cluster-size perturbations. Outside the condensations are the low density regions from whence the shells expanded. The perturbations on the amoeboid surfaces radiate outward into the low density regions and cool rapidly. Perturbations in the interior of the amoebas must radiate into their neighbors and absorb radiation from their neighbors, so they cool more slowly.

FORMATION OF POPULATION III STARS

Small, few-hundred-solar-mass perturbations cool faster than larger perturbations because they have a large surface to volume ratio. Perturbations inside the condensed regions are illuminated on all sides by radiation from other perturbations. Perturbations on the surface of the amoeba radiate efficiently into an empty hemisphere. Hundreds of thousands of diatomic hydride and hydride ion lines can transfer energy from the ultraviolet electronic bands to the infrared vibration-rotation bands, even at low abundances. Cooling and Population III star formation become easy.

FORMATION OF GLOBULAR CLUSTERS

Massive Population III stars are superluminous. They radiate about 10^{53} ergs ($10^{51}M_*/M_\odot$) in 10^6 years and then explode as supernovas. That is enough radiation for serious construction projects using radiatively-driven implosions. The words "radiatively-driven implosion" and even the concept used to be classified. When they were declassified, astrophysicists who work at the weapons laboratories could apply them to bigger problems. Simple examples of radiatively imploding a bump on the surface of a Population I molecular cloud and of radiatively imploding a small Population I cloud between two hot stars have been presented in a series of papers by Sandford, Whitaker, and Klein (Sandford, Whitaker, and Klein 1982; 1984; Klein, Sandford, and Whitaker 1983).

Figure 2 shows that a cloud between two O stars can be compressed into a dense globule in 30000 years. Figure 2 also shows open cluster formation by successive generations of implosions. Sandford, Whitaker, and Klein never extrapolated that idea to the formation of a globular cluster, but I do. A bump on a cloud that is illuminated by an O star is imploded into a dense globule by compression both from the front, and also by compression from the sides by scattered light or by dust pushed by scattered light.

These examples can be generalized to gas clouds of any population illuminated by a hot star or stars. If there is an opacity that increases non-linearly with density, the bumps on the cloud surface will be compressed and become optically thick while the surrounding gas is still optically thin and is still scattering the starlight in all directions, including behind the perturbation, as in Figure 3. The perturbation is cut off from the cloud face as a collapsing, rotating globule. The globule is further compressed by the radiation from the star and radiates excess energy from the unilluminated side that pushes the cloud away. The mass must be large enough so that the unilluminated side is in quasi-hydrostatic equilibrium or collapsing. Otherwise the globule loses mass in a wind until it evaporates. The collapse continues into a nuclear burning star. The mass of the globule and the mass of the star are determined by the optical depth scale of the perturbation in the cloud wall. The lower the opacity the greater the minimum mass required. Any leftover material in the outer shell is driven inward. The layering process repeats inward (an onion skin model) until all the matter in a large perturbation is formed into stars. Four massive stars arranged tetrahedrally will radiatively implode a one- or even a ten-million-solar mass cloud into a globular cluster. Additional hot stars accelerate the collapse. Each massive star can illuminate more than one cloud at a time. Globular clusters can be formed in any population, at any time.

Once the first Population III stars form, there is a hiatus of 10^5 to 10^6 years until they start to supernova. Before there are supernovas all gas is Population III gas. The intitial Population III stars form additional Population III stars in and around their H II regions. These new stars are smaller than the original Population III stars because of the radiatively-driven implosion. The original stars did not have external help. Because the lifetimes of Population III stars are so short, there is not enough time for larger perturbations to evolve before the Population III stars supernova. All other matter in the universe is contaminated and becomes Population II material.

Once the Population III stars start to supernova the gas becomes more and more contaminated with metals and its opacity greatly increases. Then radiatively-driven implosions form globular clusters of Population II stars that have a smaller minimum mass. The number of supernovas increases, the minimum mass continues to go down until Population II stars form that are too small to supernova, 7 or 8 $M_\odot$. These stars evolve over billions of years, lose mass, and become white dwarfs. As the supernovas continue the abundances increase above 1/100 solar and the minimum mass drops another factor of 10 or so to the point where these stars have not yet evolved off the main sequence. Many supernovas early on result in many low mass stars that evolve slowly, while few supernovas early on produce many high mass stars that evolve rapidly.

The stellar abundances and masses are determined by the number and proximity of the supernovas. The distribution function of these Population II masses is the initial mass function. The masses can range over the whole spectrum but because the Population II material has higher opacity than the Population III material, and because its collapse is helped along by external forces, the masses are smaller than the Population III masses and can even be quite small. However, the smallest Population II stars are still larger than the smallest (future) Population I stars which form easily because of high opacity gas and dust. There are Population II M dwarfs but there are no Population II brown dwarfs.

We can observe only supernovas that supernova, not the duds. There can be mass and angular momentum ranges where supernovas fail and produce oxygen and other alpha-process elements but no iron and no heavy elements. This is especially likely for Population III stars because of their large masses and rapid evolution. Duds could produce solar masses of alpha elements that would contaminate the globular-cluster-size clouds and greatly increase the opacity without increasing the iron abundance. Diatomic hydrides and oxides and their ions have millions of lines and are very efficient at radiating away excess energy. With enough oxygen it is even possible to make water with its tens of millions of lines. When most supernovas are successful, the alpha enhancement is a factor of 2 to 3 and the Fe varies from 1/100 to 1/1000 solar. These opacities are high enough to produce K dwarfs. When the condensations have relatively few successful supernovas that produce iron and many duds, the opacity becomes high enough to produce M dwarfs with alpha enhancements greater than 100 and Fe abundances 1/1000 to 1/10000 solar. With many successful supernovas and many duds the opacity becomes high enough to form M dwarfs with Fe abundances 1/300 solar but with alpha enhancements greater than 10. M dwarfs with high alpha abundances have not evolved off the main sequences in the age of the universe and are invisible for all practical purposes.

The amoeboid pseudopods of the condensations have maximum exposure and radiate most easily of all the condensed matter. I suggest that the pseudopods have so many dud Population III supernovas that most of the mass is converted into globular clusters full of M dwarfs. More than half of the mass of the universe is sequestered in invisible M dwarfs.

Globular cluster formation goes much more slowly within the amoeboid main body of the condensation. The stellar mass can vary from massive, greater than seven solar masses, down to K dwarfs greater than one half a solar mass.

FORMATION OF GALAXIES

Asymmetries in the distribution of the Population III stars around each globular-cluster-size perturbation produce a small, net globular cluster velocity. Since there are excess Population III stars at the surface of the condensed region, the globular clusters near the surface of the central condensation will be accelerated inward and will have velocities inward on the order of a fraction of a km s^{-1}. This is the radiative trigger that leads to the gravitational implosion (violent relaxation) of the systems of globular clusters into elliptical galaxies. Figure 4 shows a schematic calculation of such violent relaxation. As part of the collapse, the most energetic globular clusters are ejected into the low density regions. As galaxy-size perturbations have no symmetry, they have angular momentum and they spin up as they collapse. The globular clusters in the pseudopods either form their own galaxies around the central small cluster of galaxies, or they form a halo around it, or both.

At this point the universe is filled with small clusters of elliptical galaxies surrounded by halos of M-dwarf elliptical galaxies and globular clusters, all surrounded by low density regions. The low density regions are less than a megaparsec in diameter. All of the globular clusters in these elliptical galaxies have approximately the same age. The globular clusters collide and gain internal energy and rapidly disintegrate. By today 99.9% of them have disintegrated. The clusters that are left are not typical or representative of the properties of the initial ensemble. They are the cold tail. They are not pure, having added and lost stars through their whole lives. The current members of one of these globular clusters are not necessarily siblings, coeval, or even Population II. There can be dark globular clusters in which all or almost all the stars are neutron stars and white dwarfs. There are globular clusters of M dwarfs that have not yet evolved.

As they evolve, the elliptical galaxies with mainly high mass stars become opaque from the many supernova remnants that fill their halos. These opaque galaxies make the universe opaque. Elliptical galaxies with lower mass stars that do not supernova are transparent and faint until their stars evolve up the giant branch and lose mass.

The low density regions contain globular clusters and individual stars that originally ranged from massive to M-dwarf, neutron stars, black holes, and Population II gas blown out of galaxies and clusters and from mass loss. The low density regions also collect the alpha-enhanced M dwarfs that escape from the galaxy cluster halos. The low density regions are transparent but they can absorb radiation in lines.

Figures 5 through 12 schematically describe galactic evolution.

If the initial mass functions of the globular clusters that form an elliptical galaxy have almost all low mass stars, the galaxy remains an elliptical galaxy forever. These galaxies have low luminosity until the giant branch is strongly populated. A few, more massive, stars lose enough mass to fill the galaxy with the tenuous gas that produces the Lyman α forest.

If the initial mass functions of the globular clusters have mostly high mass stars, the elliptical galaxy evolves into a spiral galaxy. Supernova remnants and the mass lost by intermediate mass supergiants collapse into a bulge and a disk, which spin up.

An intermediate case produces an irregular or "young" galaxy.

When there is a significant high mass tail, after some 20 million years, the whole elliptical galaxy fills with supernovas and supernova remnants. The galaxy fills with jumbled magnetic structures. The galaxy becomes opaque. The supernova remnants and the magnetic structures cannot orbit because of their large collision cross-sections. They collapse into a central bulge with a quasar at the center.

Since the supernova remnants have high abundances, the bulge gas has high abundances and must form high abundance stars. This can happen both in galaxies that are today elliptical or spiral. These initial quasars continue to be powered by infall of gas that is blown off intermediate mass stars when the stars climb the giant branch. This gas is low abundance Population II gas. It dilutes the supernova remnant gas. This gas forms the disk of spiral galaxies so that the first stars in the disk have abundances initially lower than bulge abundances.

The activity that we have been describing takes place in the first 10^9 years. The time scales are set by orbital and collapse times, and by stellar evolutionary time scales. It takes, say, one orbital time to form the bulge and quasar, and a few orbital times for the mass loss infall to form the disk.

Since the disk is formed from mass-loss material from Population II stars in the halo, the mass of the disk gives a lower limit to the mass of the one- to six-solar-mass primordial Population II stars in the halo and to the number of white dwarfs. Each star loses its own mass less the mass of a white dwarf.

Since the quasar and bulge are formed from supernova remnants, the mass of the central object and bulge (less the equivalent volume of halo stars) give a lower limit to the mass of the, say, 7 solar mass and greater primordial Population II stars in the halo and to the number of neutron stars and black holes Each star loses its own mass less the mass of the neutron star or black hole.

FORMATION OF BULGES, QUASARS, DISKS, AND BARS

The massive initial Population II stars blow out most of their mass in a supernova explosion and leave a neutron star or black hole behind. The neutron stars, black holes, gas, and magnetic field remnants continue in their halo orbits. The orbits cross the plane of the galaxy and many of the orbits pass near the center. Since the gas and magnetic fields have large collision cross-sections, they interact near the center. The collisions cancel part of each component of angular momentum to produce a bulge that is a small model of the original elliptical galaxy. Since the bulge material is highly enriched in metals from the supernovas, and since it is continually shocked and compressed by collisions, it has high opacity and readily produces new massive second-generation Population II stars that rapidly implode the remaining bulge material into globular clusters with high metal abundances. In general, all of the second generation Population II stars are less massive than the corresponding initial Population II stars because the higher abundances allow the gas to radiate and collapse more readily.

Black holes, including the Population III black holes, and neutron stars orbit through all this condensing material in the bulge and they accrete some of it. They are much more likely to have gravitational interactions among themselves and with other halo stars as they pass through the bulge than when they are out in the halo. They tend to relax toward the center and to agglomerate with halo stars, bulge stars, and each other. Some of the black holes become big enough to dominate their environment. The largest black hole eventually ends up at the center of the galaxy and is orbited by the other black holes. The black holes form a second smaller model of the original elliptical galaxy and of the bulge because they have cancelled part of each component of their angular momentum, Figure 11. The black holes that orbit the central black hole are "Kerberean" black holes. They guard the central black hole by sweeping up incoming material. They collect the mass and angular momentum of all the stars, gas, low-mass black holes that fall toward the center of the galaxy. When material falls toward the center faster than the Kerberean black holes can sweep it up, it falls into the central black hole and produces a flaring that is called a quasar. If only a small amount of material falls into the center, it produces a flaring called an active galactic nucleus. When there is a collision between galaxies, material from the other galaxy can fall toward the center and also produce flaring.

The quasar can be formed only during the first few orbital periods of a galaxy because the massive stars that evolve into black holes have short lifetimes and because the remnant material is collected in the bulge when it tries to orbit through.

The mass of the bulge is proportional to the number of initial Population II stars that supernova. There is a minimum startup value because there have to be enough remnants colliding at the center to start the agglomeration. The sum of the mass of the central black hole and the Kerberean black holes is also roughly proportional to the number of Population III supernovas and intitial Population II supernovas. Massive black holes ingest a significant fraction of the metals that were produced by the Population II supernovas. Only a fraction of the black holes end up in the bulge; the remainder are still in halo orbits.

The halo is depleted of material that orbits through the bulge. Material in less eccentric orbits away from the bulge is most likely to collide and collapse as it crosses the equator. After one hundred million years, mass loss from stars that do not supernova, with masses less than seven or eight solar masses, begins. The low abundance mass-loss material, combined with remaining high abundance supernova remnant material, loses some angular momentum in all components in the collisions, but most in the x and y directions, so that it spins up. It collapses into an oblate spheroid, a thick disk, with an empty center that contains the bulge. Its diameter is much less than that of the halo. As lower mass stars evolve, the mass loss continues, and the disk grows and become more efficient at collecting mass. The newer materal forms a thin disk in the equitorial plane of the elliptical galaxy. As material continues to fall in (from evolved K dwarfs at present) the disk grows in size and structure.

The bulge repeats the evolution of the halo. The more massive stars supernova and the material falls toward the center. Orbits that pass near the center are depleted. As the lower mass stars evolve, the lost mass forms an oblate spheroid at the equator of the bulge with an empty center. If the disk has formed strong spiral arms, the spheroid becomes triaxial and forms a bar. The spheroid merges with the disk. The Kerberean black holes continue to orbit the central black hole and continue to grow.

FORMATION OF VOIDS AND THE MICROWAVE BACKGROUND

Voids and the microwave background are remnants of the radiatively-driven expansion produced by quasars. Primordial galaxies manufacture a tremendous amount of radiation. Any galaxy that is a spiral now originally had most of its mass in massive stars. A 10^{12} $M_\odot$ spiral galaxy produces, say, 10^{11} supernovas yielding 10^{62} ergs. The precurser stars radiate even more during their lifetimes, say 10^{63} ergs. There might be 3x10^{11} intermediate mass stars that radiate 10^{63} ergs and end up as white dwarfs. In addition the quasar itself produces 10^{46} to 10^{47} ergs s^{-1} for say 3x10^{8} years or about 10^{63} ergs. There is also a great deal of energy from the collapse that heats the gas and is eventually radiated away, partly by the quasar. Integrating over the first billion years, letting one-half the large galaxies be spirals, it is easy to produce 10^{51} ergs ${M_\odot}^{-1}$ averaged over all galaxies. Neutrinos produced by the supernovas add up to a similar amount of energy.

During much of the first billion years the elliptical galaxies that become spirals are filled with debris from supernovas and mass loss. They are optically thick. They self-absorb most of their own radiation and they absorb all infalling radiation from other galaxies. After the bulges and quasars collect most of the orbiting material, much of the radiation generated by the galaxies can escape, but the galaxies are still optically thick to radiation passing all the way through the galaxy from the outside, Figure 14. The galaxies still absorb all the incoming radiation. The universe is still optically thick. In this situation radiation pressure pushes the galaxies apart. Random dense groups of large galaxies with many bright quasars push themselves apart and form voids. They and smaller galaxies expand outward in a shell. The transparent galaxies are dragged along by gravity. When the quasars in smaller galaxies come on line those galaxies are already moving outward in a shell. Their radiation further increases the size of the shell and the void. The voids collide, force thinning and opening of the shells, and merge. The collisions produce streaming and galaxy clustering in the walls of the voids. The quasars eventually burn out. The gas in the halos of spiral galaxies collapses inward and begins to form the disk, leaving the halo transparent and filled with dead and unevolved stars. The elliptical galaxies are transparent and have halos filled with unevolved stars. The universe becomes optically thin. It becomes possible to see for great distances through halos and outer halos of the intervening galaxies. We can see a few of the fading quasars as they complete their job of restructuring the universe through radiatively-driven expansion.

Regős and Geller (1991) have shown that some of the small, low-density expanding regions in a uniform background will continue to expand gravitationally in an expanding universe, Figure 15. They form voids that collide and merge. The collisions produce large galaxy clusters, streaming in the void walls, and eventually large scale structure and motions that we see today. The figures will be qualitatively the same if the universe is not expanding, but instead radiation in doing the work.

The hot radiation in the ultraviolet and visible that was re-radiated in the infrared was absorbed by galaxies and pushed them apart. That radiation was eventually re-radiated in the infrared beyond 100 μm. The radiation given off by more than 10^{11} quasars became the background that we now see redshifted into the microwave. It is smooth because it averages over so many galaxies and over a long time interval. The apparent temperature turnover is caused by absorption from gas and dust at the quasar redshift that increases blueward. The background is modulated by the pattern of the voids breaking open and becoming optically thin. The pattern has nothing to do with primordial cosmology. Part of the motion detected as the microwave background dipole is a remnant of radiatively-driven streaming from void formation.

FIGURES

Figure 1. The universe is a finite cellular automaton initially "started" from a collection of ultra-massive black holes statistically uniformly distributed throughout the cellular automaton. For example, the initial state might be 10^{12} to 10^{13} 10^{13}-to-10^{14}-solar-mass black holes with average separation less than a megaparsec. The black holes explode and collide with twelve or thirteen neighbors to form amoeboid galaxy-cluster-size condensations filled with globular-cluster- and Population III-star-size perturbations. Perturbations in the pseudopods eventually form M-dwarf halos around the central condensations.

Figure 2. Simulations of radiatively-driven implosions of Population I clouds indicate the plausiblity of forming a globular cluster by surrounding a cloud with hot stars.

Figure 3. Radiation from a massive star radiatively implodes bumps on a cloud surface into stars.

Figure 4 qualitatively demonstrates that small radiative accelerations are sufficient to trigger the collapse of a universe full of globular clusters into a universe full of elliptical galaxies. I borrowed the program from Regős that she used to model void formation (Regős and Geller 1991). The universe is periodically tesselated into cubes with constant density of globular clusters, 128**3 per cube. Each cube is subdivided into 8 parallellopipeds as shown in the upper left. This is an arbitrary choice intended not to look like galaxy precursers. All the surfaces of all the parallellopipeds are given a small inward velocity as would be produced by excess supernovas at the the surfaces. The initial condition is zero gravitational force. The small motion of the surface globular clusters is enough to cause violent relaxation into a galaxy, except in one case where neighboring galaxies cause the smallest object to disintegrate and then assimilate its remains. The most energetic globular clusters are sprayed outward and escape from the galaxy cluster. They are not visible in the figure.

Figure 5. Schematic evolution of galaxy of 1/2 $M_\odot$ stars.

Figure 6. Schematic evolution of galaxy of 1 $M_\odot$ stars.

Figure 7. Schematic evolution of galaxy of 10 $M_\odot$ stars.

Figure 8. Schematic evolution of galaxy with distribution function peaking at 2/3 $M_\odot$ stars.

Figure 9. Schematic evolution of galaxy with distribution function peaking at 1 $M_\odot$ stars.

Figure 10. Schematic evolution of galaxy with distribution function peaking at 10 $M_\odot$ stars.

Figure 11. Evolution of our galaxy.

Figure 12. Isolated galaxy classification as a function of galaxy mass and of stellar mass distribution function peak. All spiral and irregular galaxies that have not been damaged by collisions or interactions have large, massive, elliptical halos.

Figure 13. There is a tremendous radiation pressure from quasars because all

their radiation is absorbed by other galaxies, the galaxies with halos filled with supernova remnants. Random groups of quasars generate enough overpressure to form voids. Transparent galaxies are dragged along by gravity.

Figure 14. Regős and Geller (1991) showed that starting with a uniform density universe, one could evolve voids and large scale structure by removing half the matter from small spheres and redistributing it in expanding shells. Even if the universe is not expanding the radiative forces are so strong that they produce the same result.

Figure 15. Table of contents of our galaxy. In addition, our galaxy is surrounded by an external halo of about 10^{13} high-alpha M dwarfs at distances greater than 100 kiloparsecs. There are between one and ten M dwarfs per square arcsecond on the sky. Their radiation is too faint to be detected. Actually the whole local cluster is imbedded in an M-dwarf halo.

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