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RADIATIVELY DRIVEN COSMOLOGY

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ABSTRACT

A Big Bang universe consisting, before recombination, of a statistically uniform gas of H, D, ^{3}He, ^{4}He, and Li ions, electrons, photons, and massless neutrinos, with density at or near the closure density, will evolve into the universe as we now observe it, with large scale structure and a smooth microwave background. 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 are formed by radiatively driven expansion. After this period the strong radiation sources are exhausted and the universe has expanded to the point where further evolution is determined by gravity and universal expansion.

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

1. INTRODUCTION

Here we present the results of innovative gedanken experiments (Kurucz 1992) in a traditional, linear, chronological sequence in the hope of stimulating research on the many topics considered.

We propose that the evolution of the universe from before recombination to the present time can be explained by simple, elementary physics. Let us start when the universe is a few hundred thousand years old, at the time when the temperature has fallen to 10000K. Let it be a statistically uniform gas consisting of H, D, ^{3}He, ^{4}He, and Li ions, electrons, photons, and massless neutrinos. Let the density be near or at the closure density. There are no peculiar velocities. There is uniform expansion and cooling. The gas is opaque. Perturbations are galaxy size. The redshift Z is greater than 1000. From this starting point the universe continues to expand and cool until the temperature drops to a few thousand degrees. The electrons combine with the ions until everything, except perhaps the Li, is neutral. The gas becomes transparent to the recombination radiation. That radiation is still visible now redshifted to the microwave. It is spatially uniform except for the redshift variation caused by our local peculiar motion.

2. FORMATION OF POPULATION III STARS

Since there is no structure and no motion, the universe must supercool through the recombination and still show the pre-recombination, galaxy-size perturbation spectrum. Perturbations that form after recombination are globular-cluster-size and superposed on the galaxy-size perturbations. There must be some difference in the spectrum of perturbations produced in maxima or minima galaxy perturbations. We assume that perturbations are smaller in mimima. A galaxy-size collection of globular-cluster-size perturbations is surrounded by extra small perturbations from the pre-recombination minimum.

No matter what the perturbation spectrum, the big perturbations will in general be surrounded by small perturbations. These might have masses as small as 100 $M_\odot$. In diameter, these are only 20 times smaller than a 10^6 $M_\odot$ perturbation and 50 times smaller than a 10^7 $M_\odot$ perturbation.

A small perturbation radiatively cools faster than a large perturbation because it has a larger surface to volume ratio. At some point H_2, HD, LiH, $H_2{}^+$, HD^+, LiH^+, H^-, etc. molecules form. These molecules radiate in the visible and infrared and quickly cool the small perturbations further. The small perturbations gravitationally collapse to form, say, 100 $M_\odot$ Population III stars. The formation of such stars has been described by Silk (1983) but the details of realistic modelling of the process are much more complicated.

Population III star formation is inherently different from all subsequent star formation because it is produced by quiescent gravitational collapse. At later times clouds have internal motions and experience external forces from shocks and radiation, all of which may promote gravitational collapse. The range of parameters (temperature, density, abundances, maximum and minimum cloud mass, maximum and minimum star mass, etc) that allow a small perturbation to quiescently gravitationally collapse into a Population III star can be determined by constructing grids of models using 3D-gravitational-radiation-hydrodynamics on larger computers than now exist.

We assume that the perturbation is a triaxial ellipsoid with a density maximum at the center that falls off monotonically and we specify the initial temperature distribution. The unrealistic case of spherical symmetry would produce an overestimate of the minimum mass cloud or star because it is more difficult for radiation to escape from a sphere. We need a mesh on the order of 256^3 to realistically treat the radiative transfer. The coordinate system is comoving with the expansion of the universe. We specify an initial redshift Z and the initial physical dimensions of the computational box at that Z. The external boundary condition is that there is radiation incident on all sides from the neighboring large perturbations. It may be necessary to compute some large perturbations first to determine their radiation fields in order to set the boundary condition. The "cosmic microwave background", at the time of Population III star formation, is somewhere in the far infrared and pumps the molecular rotational transitions. The

wavelength of the maximum shifts continuously as Z decreases. Initially, all bulk gas velocities are approximately zero, i.e., in the m s^{-1} range.

We make time-dependent statistical equilibrium calculations for every level of every atom, ion, molecule, and molecular ion (positive and negative) that can be made from H, He, and Li isotopes, and for the velocity distributions of the electrons and heavy particles. There are between 5000 and 10000 levels, including the continuum states. We include all possible bound-bound, bound-free, and free-free radiative and collisional reactions. There are between 300,000 and 400,000 lines: electronic, vibrational-rotational, and rotational. The wavelengths must be exact because fluoresence may be important. As the data do not yet exist, a preliminary step is to determine all these spectroscopic data and cross-sections. For the radiative transfer, a few times 10^6 frequencies might be sufficient to resolve the thermal Doppler profiles of each line and, if the gas starts to move, the red or blue shifts. Differential velocity shifts can greatly increase the effective opacity internal to the perturbation, while making the neighboring stationary perturbations transparent to the emitted line radiation.

We must compute a large number of models, varying the parameters. For example, the electron density and the collision rates must be sensitive to the Li abundance. It would also be possible to do the much larger calculation of a perturbation surrounded by other randomly placed perturbations to produce torquing and angular momentum as the central perturbation collapses.

3. FORMATION OF GLOBULAR CLUSTERS

Massive Population III stars are superluminous. They radiate about 10^{53} ergs in 10^6 years and then explode as supernovas. These are the only Population III stars and only their dead supernova remnants now remain, amounting to only a small fraction of the mass of the universe. Because there is not enough time for large perturbations to evolve, all other matter in the universe is contaminated by the supernovas and becomes Population II material.

The Population III stars surround globular-cluster-size perturbations. The radiative acceleration from the Population III stars produces a radiatively driven implosion of the large perturbations to form globular clusters. This happens in stages. The surface of a large perturbation is compressed and contaminated by the Population III stars. It becomes optically thick and forms a layer of Population II stars and becomes optically thin again. Simple versions of this process for radiatively imploding bumps on the surface of a molecular cloud and for radiatively imploding a small 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), but they never extrapolated the idea to the formation of a globular cluster. The layering process repeats inward until all the matter in a large perturbation is formed into stars. 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 no initial Population II brown dwarfs.

A globular cluster can be formed at any time in any population. The only requirement is the existence of hot stars surrounding and radiatively imploding a large cloud.

4. FORMATION OF GALAXIES

Asymmetries in the distribution of the Population III stars around each large perturbation produce a small, net globular cluster velocity. Since there are excess Population III stars at pre-recombination galaxy-size boundaries, the globular clusters near those boundaries will be accelerated away from the boundaries 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 of the systems of globular clusters into elliptical galaxies. As the sizes and shapes of the proto-galaxies are random, each proto-galaxy receives a small angular momentum from torquing by the other proto-galaxies as it collapses.

At this point we have a statistically uniform universe filled with elliptical galaxies. All of the globular clusters in these elliptical galaxies are 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 pure. They have 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.

Both globular cluster formation and galaxy formation produce intergalactic Population II gas and stars as leftovers or as high velocity ejecta. These stars may now be brown dwarfs, main sequence dwarfs, luminous giants, white dwarfs, or neutron stars. Galaxy formation also produces intergalactic globular clusters because high velocity clusters can be ejected in the violent relaxation.

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.

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 that produces supernovas, the supernova remnants can no longer 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 either in an elliptical galaxy or a spiral galaxy. 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 stars in the disk have abundances initially lower than bulge abundances. The oldest population of stars in the disk suffers many globular cluster collisions, so it is dispersed into a thick disk.

The quasars eventually run out of fuel. If later the fuel is replenished, say by galaxy-galaxy collisions, the quasar can re-ignite.

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.

5. FORMATION OF VOIDS

Next we consider radiatively driven expansion. Primordial galaxies produce 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}- 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. If half the large galaxies are 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 the first billion years galaxies are much closer together than now. If that era corresponds to redshifts of say z=10 to z=5, galaxies are between 11 and 6 times closer than now. Statistically it is possible for a large group of galaxies (say 10^5) to be optically thick to their own radiation (except for radio). Any photon emitted at the center passes through so many spiral galaxies that it must be absorbed. Thus the clump of galaxies expands from its own radiation pressure. Galaxies with high projected opacity-to-mass ratios, perhaps face-on spirals, are accelerated the most, followed by all the other spirals. The elliptical galaxies are dragged along by gravitational attraction. A low density region forms

and continues to expand from radiation pressure as long as the galaxies are very bright and until the clump of galaxies becomes optically thin. The expansion of the universe eventually guarantees the latter. Eventually the role of radiation becomes insignificant compared to gravity.

Regős and Geller (1991) have shown that some of the small, low-density expanding regions in a uniform background will continue to expand gravitationally as the universe expands. They form voids that collide and merge. The collisions produce galaxy clusters, streaming in the void walls, and eventually the large scale structure that we see today.

6. CONCLUSIONS

A Big Bang universe consisting, before recombination, of a statistically uniform gas of H, D, ^{3}He, ^{4}He, and Li ions, electrons, photons, and massless neutrinos at a density sufficient, or nearly sufficient, to produce a flat universe, will evolve into the universe as we now observe it, with large scale structure and a smooth microwave background. Evolution during the first billion years is controlled by radiation.

The universe has evolved as follows since recombination:

1) small perturbations formed superluminous Population III stars whose radiation caused

2) large perturbations to implode and form globular clusters of Population II stars, and then

3) systems of globular clusters suffered radiatively triggered collapse into elliptical galaxies, some of which

4) evolved to form quasars and spirals that

5) gave off so much radiation that, in some places, statistically, voids were formed by radiation pressure, and then

6) void collisions and void walls produced clusters of galaxies and the large scale flows and structure that we see today.

The number of Population III stars was very small and they all exploded so that only remnants are left. Essentially all matter has been processed in stars. Only initial Population II stars have any chance of still having significant primordial lithium. Because the baryon density is much higher than commonly assumed in Big Bang cosmologies, the primordial lithium abundance is also much higher; $\log(N_{Li}/N_{total})$ greater than 3 instead of 2.1 as observed. This is the only discrepancy with observation produced by radiatively driven cosmology. Either the determination of the lithium abundance is wrong in extreme Population II stars, or the lithium has been depleted in some way by a factor of 10 and is not primordial.

The interstellar medium was produced by stars. The intergalactic medium was produced by galaxies. It is not primordial.

All galaxies that have not been damaged by collisions or interactions have large, massive, elliptical halos.

Our own galaxy has a halo containing about 10^{11} neutron stars, $3x10^{11}$ white dwarfs, visible K and M stars, and 10^{11} slightly evolved low mass stars (all numbers to astronomical accuracy). It also has over 10^2 coeval globular clusters that are the remnants of 10^6 primordial globular clusters from which our galaxy was formed. There is a central, inactive, quasar surrounded by a bulge of high abundance Population II stars. Both were made from the first Population II supernova remnants which collapsed from the halo to the center of the galaxy. The disk was made from gas lost by intermediate mass Population II stars in the halo when they evolved up the giant branch, and that gas subsequently collapsed into the disk and spun up to conserve angular momentum. Thus the disk has lower abundances than the bulge, even though it was formed later. There were still many globular clusters at the time of disk formation so many disk stars were scattered by collisions with globular clusters and formed a thick disk population. There are stars in the halo and globular clusters that were formed in the disk or bulge and were accreted by globular clusters and carried into the halo. The stars in globular clusters need not be siblings, coeval, or Population II. Non-primordial globular clusters could have been formed in the bulge, the disk, or in collapsing gas clouds.

There is no inconsistency between a smooth universe before recombination that creates the microwave background and the large scale structure that we see today because there has been a phase change. During the first billion years evolution was controlled by changing matter into radiation in massive stars. Gravity became dominant only after these initial bursts of radiation were exhausted.

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