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Thermal Instabilities in Protogalactic Clouds

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The means by which a protogalaxy can fragment to form the first generation of stars and globular clusters remains an important problem in astrophysics. Gravitational instabilities grow on timescales too long to drive fragmentation before the background density grows by many orders of magnitude (see Murray and Lin 1989a, and references therein). Thermal instability provides a much more likely mechanism. After its initial collapse, a protogalactic cloud is expected to be shock heated to its virial temperature $\sim 10^6$ K. Cooling by H and He^+ below 10^6 K has a negative slope, so that the cloud is subject to strong thermal instabilities. Density enhancements may then grow rapidly, fragmenting the protogalaxy as it cools to lower temperatures.

Two possible outcomes exist for the final masses of the fragments resulting from thermal instability. Which will occur depends upon the importance of cooling by H_2. Previous studies which assumed equilibrium cooling (e.g. Fall and Rees 1985) have concluded that perturbations will grow until their temperatures reach 10^4 K, at which point atomic cooling stabilizes, while the H_2 abundance is still small. This halts cooling and the growth of perturbations. The resulting temperatures and densities lead to Jeans masses in the appropriate range for proto-globular clusters.

Cooling is so efficient above 10^4 K, however, that the cooling time scale drops below the recombination time scale. Ionization fractions will therefore be significantly higher than in equilibrium, leading to much more efficient cooling. Studies which account for non-equilibrium ionization fractions (Palla and Zinnecker 1987; and Shapiro and Kang 1987) find that atomic cooling can proceed to temperatures ≈ 6000 K. The lower temperatures and higher ionization fractions increase the formation rate of H_2 above its equilibrium value. Molecular cooling can then lead to temperatures ~ 100 K. The end result may be to form a generation of primordial (Population III) stars, rather than protoclusters.

The ~~studies above do not, however,~~ consider the role of dynamical effects upon the growth of perturbations. This is done in the current study. The method used is similar to that used in Murray and Lin (1989a; see also the *Erratum* to appear September 15), which examined the growth of thermal instabilities with a one-dimensional Lagrangian hydrodynamics code, written for spherical symmetry. Perturbed regions therefore take the form of shells. The dynamical variables are integrated explicitly, while the temperature, ionization fraction, and molecular fraction are integrated implicitly, and account is taken for non-equilibrium values of these quantities.

Perturbations with non-negligible initial amplitudes develop large contrasts with the background protogalaxy with which they maintain pressure equilibrium. The resulting high densities enhance the formation of H_2 (assumed to form in the gas phase via H^-), which then leads to rapid cooling down to 100 K. The resulting Jeans mass is well below the characteristic mass scales of globular clusters. These perturbations, therefore, would lead to the formation of Population III stars, not clusters.

The evolution is different only for perturbations with very small ($\lesssim$0.5%) initial amplitudes. They do not undergo a strong thermal instability, and so do not cool significantly ahead of the protogalaxy. They do not, therefore, develop large density contrasts with the background, leading to long formation timescales for H_2, so that the cooling efficiency remains small. These perturbations, therefore, remain near 10^4 K, becoming density-enhanced regions in a protogalaxy of the same temperature. Their subsequent evolution depends upon whether the perturbed regions encompass more or less than a Jeans mass ($\sim 10^7 M_\odot$). In the former case, the condensation will continue to contract, while it will re-expand in the latter case. Either motion will occur on a dynamical timescale for the perturbed region, $\sim 10^{15}$ s. This timescale is sufficiently long that the protoclusters resulting from this evolution will be subject to contamination by a first generation of massive stars, after which they will evolve to form stars as discussed by Murray and Lin (1989a,b). The large Jeans mass would lead to difficulty forming bound stellar clusters. Cooling by contaminating metals may, however, reduce the Jeans mass significantly.

As discussed by Fall and Rees (1985), photodissociation of H_2, or photoionization of H^- by hard photons from the background gas, hot stars, or an active galactic nucleus can also act to prevent cooling below 10^4 K, and therefore enhancing the formation of protoclusters relative to stars. Which process will dominate, and the necessary luminosity, depends upon the spectrum of hard photons. A broad spectrum, where much of the energy is at lower energies, near the maximum of the H^- cross section, will lead to photoionization of H^- being the dominant process. The critical luminosity for this process to reduce the H_2 abundance below that necessary for further cooling is $\sim 10^{43}$ ergs s^{-1}. If the spectrum is concentrated at higher energies, photodissociation will dominate, and the critical luminosity is $\sim 10^{45}$ ergs s^{-1}. The role of high energy photons may form an explanation for the observed variation of the specific frequency of globulars with galactic environment, being higher for galaxies in rich clusters, where x-ray heating at early times would be expected to be more important.

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