Star Formation and the Evolution of the Protogalactic Medium

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Either during the initial collapse of a protogalactic cloud into a dark matter potential, or during a merger between two galaxies, large amounts of gas is shock heated to the virial temperature of the system ($\sim 10^6$ K). This can only hold until the density reaches a point at which the gas can cool on a timescale shorter than the dynamical timescale of the system. At this density, overdense regions of the hot gas cool in a runaway process, due to the shallow temperature dependence of cooling by bremsstrahlung emission.

In the presence of strong ultraviolet sources, the cooling of the overdense regions halts at 10^4 K, resulting in the formation of a population of warm clouds. At low gas densities, sufficient ultraviolet flux may result from background AGN's. For most densities, however, hot stars within the galaxy are required.

In the absence of UV heating, cooling continues to temperatures of 100 K or below. This occurs even in the absence of any metals, due to the efficient formation of H_2 via H^- in the gas phase. In cases where this occurs, the result is the formation of a population of cold clouds.

The system rapidly achieves an equilibrium among the three phases. Heating of the hot phase is primarily due to the release of gravitational energy as the warm clouds (which make up most of the mass of the system) settle into the gravitational potential. Two mechanisms contribute to cooling the hot phase. At high densities, cooling is dominated by bremsstrahlung emission. Energy is also lost from the hot phase by conduction into the warm clouds, which, due to their high densities, lose the incoming energy rapidly via radiation. Conductive losses dominate the cooling of the hot phase at low densities.

The clouds in the warm phase are heated primarily by UV radiation from nearby, hot stars, and are cooled by emission from metal ions and H_2. The distribution of the warm clouds is determined by a combination of factors. The minimum size of the clouds is determined by the size of those clouds which are just able to radiate away the energy conducted into them from the hot phase. The maximum cloud size is determined by the Bonner-Ebert condition for gravitational instability. Clouds of all sizes lose mass, due to Kelvin-Helmholtz instability, resulting from their motion through the hot phase, and due to star formation. The clouds gain mass both from mergers with other clouds, and from condensation from the hot phase.

Cold clouds form wherever the UV heating is insufficient to maintain the warm clouds at 10^4 K. Stars form rapidly within them. At low metallicities, cooling cannot proceed to temperatures significantly below about 100 K. At such high temperatures, the formation of massive stars is preferred, which form copious sources of UV emission, helping to maintain nearby warm clouds at 10^4 K. Star formation is, therefore, a self-regulating process, with stars forming at just the rate needed to maintain the warm phase.

We have performed numerical models, focussing upon the evolution of the hot phase. The warm phase is treated approximately, with the assumption that the clouds follow a power-law distribution in radius, with the exponent independent of position in the galaxy. The cold phase is not treated explicitly. Rather, it is assumed that, when gas cools from the warm phase, it instantaneously passes through the cold phase to form stars.

The hot and warm phases are modeled as separate fluids using a one-dimensional hydrodynamics code. The warm clouds are assumed to fall into the dark matter potential, reaching their terminal velocities, and heating the hot phase by their motions. Both bremsstrahlung and conductive cooling of the hot phase is included. Whenever cooling exceeds heating in the hot phase, mass is gradually transferred (on the net cooling timescale) from the hot to the warm phase. Mass is removed from the warm phase to form stars at a rate determined by the criterion for self-regulation.

Models have been considered in which the power-law of the warm phase is such that the distribution is dominated by either the most or least massive clouds. In the former cases, we find the resulting pressures of the hot phase to be comparable to those inferred for the young Galaxy from the properties of globular clusters. The fit is especially good in models in which heating is less efficient, due to slower net motions of the warm clouds, or due to a smaller circular speed, as might be expected if the Galactic potential has deepened with time. In a model dominated by small clouds, the slower terminal speeds reduced the heating significantly, while the larger surface area increased the cooling, leading to the filling factor of the warm phase increasing to unity.

The stellar distributions resulting from the models are significantly steeper than the gas distributions. This is a natural result of the self-regulation mechanism, which leads directly to a star formation rate that varies with the square of the gas density.

In future work, we shall explore more fully the physical factors that determine the size distribution of the warm clouds, and the possibility that conductive cooling of the hot phase may explain the observed lack of x-ray haloes around young galaxies at high redshift.