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Radiation-Hydrodynamical Simulations of Primordial Galaxy Formation in the UV Background

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Abstract. We study the effects of the ultraviolet background radiation (UVB) on the formation of primordial galaxies, solving self-consistently radiative transfer of photons, non-equilibrium H_2 chemistry, and one-dimensional hydrodynamics. The cut-off scale of collapse is shown to drop significantly compared to previous optically thin predictions, due to both self-shielding of the gas and H_2 cooling. For plausible radiation intensities and spectra, the collapsing gas can cool efficiently to temperatures well below 10^4K before rotationally supported. Our results imply that star formation can take place in low-mass objects collapsing in the UVB.

1. Introduction

It is widely recognized that the UVB has prominent impacts on galaxy formation. Several authors suggested that the collapse of subgalactic objects is suppressed via photoionization and heating by the UVB (e.g., Umemura & Ikeuchi 1984; Efstathiou 1992; Thoul & Weinberg 1996; Kepner, Babul & Spergel 1997). Most previous studies, however, assumed for simplicity that the medium is optically thin or static. Self-shielding against the UVB and dynamical evolution are of particular importance in assessing correctly the final states of these objects.

Star formation in primordial galaxies is greatly regulated by hydrogen molecules (H_2), which is the only coolant to $T < 10^4$K in the metal-poor gas (e.g., Peebles & 1968). Formation and destruction of H_2 are sensitive to the presence of radiation (Stecher & Williams 1967; Haiman, Rees & Loeb 1997) and must also be coupled with accurate treatment of radiative transfer.

In this paper, we attempt to implement an accurate radiation-hydrodynamical calculation on the evolution of primordial galaxies, solving self-consistently radiative transfer of photons, non-equilibrium H_2 chemistry, and one-dimensional hydrodynamics. We investigate possibilities of collapse and star formation and

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discuss their cosmological implications. Details of the analyses are published in Kitayama et al. (2001).

2. Model

We simulate the evolution of a spherical cloud exposed to the external UVB. The cloud is composed of gas and dark matter. At each time-step, direction/frequency-dependent radiative transfer is solved taking account of both absorption and emission of ionizing photons. Non-equilibrium chemical reactions are solved simultaneously for the species e, H, H^+, H^-, H_2 and H_2^+. Photodissociation of H_2, H_2^+ and H^- are also taken into account. Simulations are started when the overdensity of a cloud is still in the linear regime, and halted when the gas shell collapses to 1/30 of the turn-around radius. This is the scale below which the gas is supposed to attain rotational support and the approximation of spherical symmetry breaks down.

3. Results and Discussion

The present radiation-hydrodynamical calculations provide accurate predictions for the collapse of primordial galaxies. Although the UVB does suppress the collapse of low-mass objects, the negative feedback turns out to be weaker than previous optically thin predictions (e.g., Thoul & Weinberg 1996). In particular, the cut-off scale of collapse falls significantly below the virial temperature $T_{\rm vir} = 10^4$K at weak UV intensities due to both self-shielding of the gas and H_2 cooling. Objects above this threshold undergo run-away collapse and do not settle into hydrostatic equilibrium. For plausible values of radiation intensity, the gas at the cloud center can cool efficiently to temperatures well below 10^4K before rotationally supported and the final H_2 fraction reaches $\sim 10^{-3}$.

Our results imply that star formation can take place in low-mass objects collapsing in the UVB. The threshold baryon mass for star formation is $\sim 10^9 M_\odot$ for clouds collapsing at redshifts $z < 3$, but drops significantly at higher redshifts. In a conventional cold dark matter universe, the latter coincides roughly with that of the 1σ density fluctuations. Objects above this threshold can thus constitute 'building blocks' of luminous structures observed today.

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