The Dawn of Galaxies

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Abstract. The development of primordial inhomogeneities into the non-linear regime and the formation of the first astrophysical objects within dark matter halos mark the transition from a simple, neutral, cooling universe – described by just a few parameters – to a messy ionized one – the realm of radiative, hydrodynamic, and star formation processes. The recent measurement by the *WMAP* satellite of a large optical depth to electron scattering implies that this transition must have begun very early, and that the universe was reionized at redshift $z_{\rm ion} = 17 \pm 5$. It is an early generation of extremely metal-poor massive stars and/or 'seed' accreting black holes in subgalactic halos that may have generated the ultraviolet radiation and mechanical energy that reheated and reionized most of the hydrogen in the cosmos. The detailed thermal, ionization, and chemical enrichment history of the universe during the crucial formative stages around $z = 10 - 20$ depends on the power-spectrum of density fluctuations on small scales, the stellar initial mass function and star formation efficiency, a complex network of poorly understood 'feedback' mechanisms, and remains one of the crucial missing links in galaxy formation and evolution studies.

1 Introduction

The last decade has witnessed great advances in our understanding of the high redshift universe. The pace of observational cosmology and extragalactic astronomy has never been faster, and progress has been equally significant on the theoretical side. The key idea of currently popular cosmological scenarios, that primordial density fluctuations grow by gravitational instability driven by cold, collisionless dark matter (CDM), has been elaborated upon and explored in detail through large-scale numerical simulations on supercomputers, leading to a hierarchical ('bottom-up') scenario of structure formation. In this model, the first objects to form are on subgalactic scales, and merge to make progressively bigger structures ('hierarchical clustering'). Ordinary matter in the universe follows the dynamics dictated by the dark matter until radiative, hydrodynamic, and star formation processes take over. Perhaps the most remarkable success of this theory has been the prediction of anisotropies in the temperature of the cosmic microwave background (CMB) radiation at about the level subsequently measured by the *COBE* satellite and most recently by the *BOOMERANG*, *MAXIMA*, *DASI*, *CBI*, *Archeops*, and *WMAP* experiments.

In spite of some significant achievements in our understanding of the formation of cosmic structures, there are still many challenges facing hierarchical clustering theories, and many fundamental questions remain, at best, only partially

ESO Symposia: Multiwavelength Mapping of Galaxy Evolution and Formation, pp. 1–11, 2005.

answered. While quite successful in matching the observed large-scale density distribution (like, e.g., the properties of galaxy clusters, galaxy clustering, and the statistics of the Lyman-α forest), CDM simulations appear to produce halos that are too centrally concentrated compared to the mass distribution inferred from the rotation curves of (dark matter-dominated) dwarf galaxies, and to predict too many dark matter subhalos compared to the number of dwarf satellites observed within the Local Group.[38,53,37,27] Another perceived problem (possibly connected with the 'missing satellites'[8]) is our inability to predict when, how, and to what temperature the universe was reheated and reionized, i.e. to understand the initial conditions of the galaxy formation process. While N-body+hydrodynamical simulations have convincingly shown that the intergalactic medium (IGM) – the main repository of baryons at high redshift – is expected to fragment into structures at early times in CDM cosmogonies, the same simulations are much less able to predict the efficiency with which the first gravitationally collapsed objects lit up the universe at the end of the 'dark ages'. The crucial processes of star formation, preheating and feedback (e.g. the effect of the heat input from the first generation of sources on later ones), and assembly of massive black holes in the nuclei of galaxies are poorly understood.[30] We know that at least some galaxies and quasars were already shining when the universe was less than 10^9 yr old. But when did the first luminous objects form, what was their nature, and what impact did they have on their environment and on the formation of more massive galaxies? While the excess H I absorption measured in the spectra of $z \sim 6$ quasars in the Sloan Digital Sky Survey (SDSS) has been interpreted as the signature of the trailing edge of the cosmic reionization epoch[3,17,15], the recent detection by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) of a large optical depth to Thomson scattering, $\tau_e = 0.17 \pm 0.04$ suggests that the universe was reionized at higher redshifts, $z_{\rm ion} = 17 \pm 5$.[28,51] This is of course an indication of significant star-formation activity at very early times.

In this talk I will summarize some recent developments in our understanding of the dawn of galaxies and the impact that some of the earliest cosmic structure may have had on the baryonic universe.

2 The Dark Ages

In the era of precision cosmology we know that, at a redshift $z_{\rm dec} = 1088 \pm 1$, exactly $t_{\rm dec} = (372 \pm 14) \times 10^3$ years after the big bang, the universe became optically thin to Thomson scattering[51], and entered a 'dark age'.[42] At this epoch the electron fraction dropped below 13%, and the primordial radiation cooled below 3000 K, shifting first into the infrared and then into the radio.

We understand the microphysics of the post-recombination universe well. The fractional ionization froze out to the value $\sim 10^{-4.8}\Omega_M/(h\Omega_b)$: these residual electrons were enough to keep the matter in thermal equilibrium with the radiation via Compton scattering until a thermalization redshift $z_t \simeq 800(\Omega_b h^2)^{2/5} \simeq 150$, i.e. well after the universe became transparent.[40] Thereafter, the matter