Modeling the Multi-Wavelength Universe: The Assembly of Massive Galaxies

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Abstract. Pan-chromatic galaxy surveys are providing tightening constraints on the global mass assembly history, and high-resolution imaging of large fields is telling us when and where stars were formed. How well are state-of-the-art hierarchical galaxy formation models currently doing at reproducing these observations? I present results here that suggest that hierarchical models are doing quite well at reproducing the *global* star formation and stellar mass assembly history obtained from galaxies selected in the optical and Near IR. However, the same models fail to reproduce two very important populations at high redshift: quiescent red spheroids and vigorously star-forming, dust-enshrouded starbursts. This mismatch carries important lessons about how star formation is triggered and regulated in early galaxies, and may force us to consider new ideas about the formation of massive spheroids.

1 Tracing Galaxy Assembly

Probing the high-mass end of the galaxy mass function at any epoch provides a particularly strong test of theories of galaxy formation. A zoo of apparently massive objects at high redshift has been discovered in recent years, in a broad range of wavelengths and utilizing a variety of selection techniques. For example, at this meeting, we heard about massive galaxies at $z \sim 1$ in the COMBO-17/GEMS survey (Bell, Rix), VIMOS (Le Fevre), and DEEP (Koo, Newman), near IR selected galaxies and Extremely Red Objects (EROs) at $z \sim$ 1–2 (Fontana, Daddi, Drory, Cimatti), color-selected galaxies in the spectroscopic redshift 'desert' at $z \sim$ 1.5-2.5 (Steidel, Chen), and sub-mm and mm selected galaxies at $z \sim 2.5$ (Chapman, Bertoldi, Genzel). The challenge posed to us by the multi-wavelength universe is to unify this zoo of objects into a coherent picture of galaxy evolution.

Another exciting observational development is the imaging of relatively large fields with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST), combined with multi-wavelength ground-based observations. These new surveys, such as GOODS (Great Observatories Origins Deep Survey), GEMS (Galaxy Evolution from Morphology and SEDs), and COSMOS, will for the first time allow us to study the connection between galaxy morphology (through structural parameters such as bulge-to-disk ratio) and stellar populations (through broad band colors and spectroscopy) for a statistically meaningful sample, over a large range of cosmic time. We can then go beyond a global census of star formation or the build-up of stellar mass, to understand *where and how* stars were formed, and perhaps which processes stimulated or regulated star formation. In this paper, I shall attempt to briefly summarize the status of our

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theoretical understanding of some of these observational results and what we may learn about galaxy formation from them.

2 Do Massive Galaxies at High Redshift Pose a 'Crisis' for CDM?

It has become a familiar story: in the Cold Dark Matter (CDM) model of structure formation, small mass objects form first, and larger mass objects form hierarchically through mergers and accretion. Therefore, measurements of the number density of massive structures at high redshift pose *potentially* strong constraints on this class of models. The extent to which this potential is realized, however, depends on how massive and how common are the objects at any given epoch. Moreover, such arguments also require making a connection between an observed population and the dark matter halos in which they are expected to reside. For most, if not all, of the populations mentioned above, this is far from straightforward. It is a common perception that the detection of massive galaxies at high redshift is a serious problem for CDM. It is interesting to take a step back for a moment from the complexities of modeling gas physics, star formation, feedback, radiative transfer, stellar populations, etc., and to simply ask whether the 'concordance' ΛCDM model produces enough massive *dark matter halos* to plausibly host the objects that have been detected.

This simple exercise is carried out in Fig. 1, which shows the predicted cumulative comoving number density of dark matter halos above a given mass, from 10^{11}–$10^{15}\,M_\odot$ as labeled, as a function of redshift[1]. These were obtained from the Sheth-Tormen modified Press-Schechter model [28]. Also shown are the estimated comoving number densities of various observed populations, as described in the figure caption. It has been claimed that the sub-mm galaxies, EROs and K20 $z \sim 2$ objects have stellar masses of a few times $10^{11} M_\odot$ [6,15,23,10]. Making the plausible assumptions that about fifteen percent of the total mass is in the form of baryons, and a few tenths of the baryons are in stars, one can easily accommodate the observed numbers of objects within suitably massive dark matter halos of $\sim 10^{13} M_\odot$. The Lyman break galaxies, which are more numerous but probably have stellar masses about an order of magnitude smaller (a few times $10^{10} M_\odot$; [27,24]) are also easily accommodated within halos of a few times $10^{11} M_\odot$. Even the $z \sim 6$ quasars detected by SDSS [13], which must harbor black holes of $\sim 10^9 M_\odot$ if they are Eddington limited, can be easily accommodated within $10^{13} M_\odot$ halos (see [5] for more detailed modeling of these objects). So far, none of the observed populations poses a *fundamental* problem for concordance ΛCDM. Had the observed number density of $10^{11} M_\odot$ galaxies at $z \sim 2$ been an order of magnitude higher than the current estimates, theorists would have good cause to squirm. As it is, these results suggest that there were fewer massive galaxies in the past, in qualitative agreement with hierarchical

[1] All results presented in this paper assume the 'concordance' ΛCDM cosmology: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$ km/s/Mpc, σ_8=0.9.