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Galaxy Formation

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Abstract. I summarize current knowledge of galaxy formation with emphasis on the initial conditions provided by the ΛCDM cosmology, integral constraints from cosmological quantities, and the demographics of high-redshift protogalaxies. Tables are provided summarizing the number density, star formation rate and stellar mass per object, cosmic star formation rate and stellar mass densities, clustering length and typical dark matter halo masses for Lyman break galaxies, Lyman alpha emitting galaxies, Distant red galaxies, Sub-millimeter galaxies, and Damped Lyman α absorption systems. I also discuss five key unsolved problems in galaxy formation and prognosticate advances that the near future will bring.

1. Boundary Conditions for Galaxy Formation

1.1. Initial Conditions: ΛCDM Cosmology

The initial conditions for the formation of galaxies are provided by the now-standard ΛCDM cosmological model. The combined results of the WMAP satellite study of Cosmic Microwave Background anisotropies, large-scale structure, and Type Ia supernovae observations yield best-fit values for the cosmological parameters of roughly $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $\Omega_b = 0.04$, and $H_0 = 70h_{70}$km s^{-1} Mpc^{-1} (Bennett et al. 2003).[1] The original model of galaxy formation was Monolithic Collapse (Eggen, Lynden-Bell, & Sandage 1962), where gravitational collapse of a cloud of primordial gas very early in the lifetime of the Universe formed all parts of each galaxy at the same time. Modern evidence rules out this model on two fronts; the widely varying ages of different components of the Galaxy provide a counter-example, and the ΛCDM cosmology predicts "bottom-up" i.e. hierarchical rather than "top-down" structure formation.

Hierarchical structure formation is a generic feature of Cold Dark Matter (CDM) models. Small overdensities are able to overcome the cosmological expansion and collapse first, and the resulting dark matter "halos" merge together to form larger halos which serve as sites of galaxy formation. This process continues until the present day, making galaxy formation an ongoing process. The nearly-scale-invariant primordial power spectrum inferred from combining WMAP with large-scale structure observations provides power on all scales in

[1] We include h_{70}, analogous to the traditional parameter $h \equiv h_{100}$, even though its value appears quite close to 1.

the distribution of CDM. The baryons fall into the CDM potential wells after decoupling, leaving only trace evidence of their previous acoustic oscillations as a series of low-amplitude peaks in the matter power spectrum. The non-linear collapse of dark matter overdensities occurs on larger and larger scales, so the typical collapsed halo mass grows with time, but no preferred scale is introduced. ΛCDM therefore provides a distribution of halos where galaxies can form, with the details of the process up to baryonic physics.

Despite the lack of preferred galaxy scales in the distribution of dark matter halos, baryonic physics causes galaxies to have minimum and maximum masses. The maximum mass is that of CD galaxies in cluster centers with baryonic masses $\sim 10^{12}\mathrm{M}_\odot$ and virial masses $\sim 10^{13}\mathrm{M}_\odot$; there are $\sim 10^{14}\mathrm{M}_\odot$ of baryons available in a rich cluster but virialization of galaxies and heating of gas to the high virial temperature prevent most of this mass from finding its way to the central galaxy. The minimum mass observed today is that of dwarf galaxies, $\sim 10^{8}\mathrm{M}_\odot$, but galaxies may initially have formed as small as $10^{6}\mathrm{M}_\odot$ (the baryonic Jean's mass after recombination i.e. the minimum mass for which gravity overwhelmed pressure support). Explaining the lack of observed galaxies with circular velocities below 30 km/s is a major goal; it is suspected that feedback from supernovae explosions may have quenched star formation in such low-mass objects immediately after a single burst of star formation (Dekel & Silk 1986).

The growth of cosmological structure and collapse of dark matter halos is a feature of the matter-dominated epoch. During radiation-domination, perturbations on scales smaller than the sound horizon were unable to grow due to acoustic oscillations in the photon-baryon fluid that gave rise to the famous peaks in the CMB angular power spectrum and the lower-amplitude peaks in the matter power spectrum. Now that we have entered a phase of dark energy domination, structure growth is slowing and will cease entirely as the universe enters a new phase of inflation. This cosmological "freeze-out" in structure formation is recent, since equality between the dark energy and matter densities occurred at $z_{eq} = 0.4$. The slowing of structure formation occurs gradually, so the growth of cosmological structure continued nearly unabated until z_{eq}, even though we see strong observational evidence for "downsizing" at $z < 1$ where high-mass galaxies grow far more slowly than lower-mass galaxies (e.g. Treu et al. 2005; Smith 2005). Another term being used by some is "anti-hierarchical", which is basically a synonym for "downsizing" but seems to imply inconsistency with hierarchical cosmology. However, the observed freeze-out in galaxy (and possibly supermassive black hole) formation in massive galaxies is not inconsistent with CDM models; rather, it appears to be caused by baryonic feedback which is not well understood at present (see §6.). The slowing of cosmological structure growth since $z \simeq 0.4$ may, however, play a role in the recent decline of the cosmic star formation rate density discussed by Bell et al. (2005).

1.2. Final Conditions: Low-redshift Galaxies

The study of galaxy formation is made easier by having full boundary conditions. The final conditions are the Hubble sequence of mature galaxies we see in the nearby universe at redshift zero. Indeed, much has been learned about galaxy formation from "archaeological" evidence in the ages and chemical abundances of various Galactic stellar populations, and expanding these studies to the rest of the Local Group and beyond is quite useful. Nonetheless, there are great advantages to observing galaxies in the act of formation, which motivates the study of high-redshift galaxies. At $z > 2$, galaxy-mass halos are rare so the majority of galaxies we observe reside in dark matter halos that have only recently collapsed i.e. at high-redshift most galaxies are young. In this sense, $z > 2$ can be considered the epoch of galaxy formation.

2. Integral Constraints: Cosmological Quantities

Instead of studying galaxies as discrete objects residing in dark matter halos, one can track the cosmological quantities that comprise the baryon budget. Galaxy formation and evolution plays the fundamental role in the processing of baryons from neutral hydrogen to molecular gas to stars to metals. Star formation is inextricably linked with galaxy formation; whether you choose to define a galaxy as a large conglomeration of stars or an overdensity of baryons inside a collapsed dark matter halo, the galaxies in our universe form great numbers of stars. The cosmological quantities of interest provide integral constraints on star formation. The cosmic star formation rate density (SFRD) is an integral constraint averaged over the volume of the universe observable at a given redshift. The cosmic density of neutral gas, Ω_{gas}, the cosmic density of metals, Ω_Z, and the cosmic stellar mass density all provide integral constraints on the SFRD over time, as will be discussed below. The sum of the cosmic infrared background (CIB) and cosmic far-infrared background (FIRB) radiation provides an integral constraint on the SFRD from the Big Bang all the way to $z = 0$ by tracing the energy generated by nuclear reactions in stars.

2.1. Cosmic Density of Neutral Gas

The Damped Lyman α Absorption systems (DLAs, Wolfe et al. 1986) are quasar absorption line systems with HI column densities $\geq 2 \times 10^{20}\mathrm{cm}^{-2}$, sufficient to self-shield against the high-redshift ionizing background. Studying quasar absorption-line spectra provides a (nearly) unbiased sample of lines-of-sight through the cosmos ideal for measuring cosmological quantities. The DLAs have been found to contain the majority of neutral hydrogen atoms at high redshift (see the recent review by Wolfe, Gawiser, & Prochaska 2005). Moreover, DLAs contain the vast majority of neutral gas, by which we mean neutral hydrogen and helium in regions that are sufficiently neutral to cool and participate in star formation, as lower column density systems are predominantly ionized. Hence the DLAs provide the reservoir of neutral gas that is available for star formation. In a simple closed box model, $d\rho_{gas}/dt = -d\rho_*/dt$, and the net decrease in the cosmic density of neutral gas from $z = 3$ to $z = 0$ is assumed to have all been turned into stars (see Fig. 5 of Wolfe et al. 2005). In that case, the DLAs appear to have formed about half of the stars seen in galaxies today. The truth is more complicated in hierarchical cosmology, where an open box model must be used;

$$\frac{d\rho_{gas}}{dt} = -\frac{d\rho_*}{dt} + \mathrm{infall} + \mathrm{merging} - \mathrm{winds}. \tag{1}$$

Cosmological models for infall of gas from the intergalactic medium (IGM), merging of lower column-density systems, and gas loss due to galactic winds are still quite uncertain, but the star formation rates actually measured for DLAs (Wolfe, Gawiser, & Prochaska 2003a; Wolfe, Prochaska, & Gawiser 2003b, Wolfe et al. 2004) imply that DLAs could have formed all present-day stars. Unfortunately, large uncertainties in the source and sink terms prevent us from using changes in the cosmic density of neutral gas as an integral constraint on the cosmic SFRD at the present time.

2.2. Star Formation Rate Density

The cosmic star formation rate density has now been measured out to $z \simeq 6$ (Giavalisco et al. 2004). The high-redshift points are taken from only the Lyman break galaxies, and it is unclear how severe the resulting incompleteness is since we are not sure if all star-forming galaxy populations at these redshifts are known. The plot is traditionally shown in misleading units of $M_\odot Mpc^{-3} yr^{-1}$ versus redshift; in order to integrate-by-eye, one should plot this quantity versus time, and this has the effect of greatly increasing the apparent amount of star formation at low redshifts. Despite significant uncertainties in the SFRD at $z > 3$ due to incompleteness and large dust corrections, it appears that most stars in the present-day universe formed at $z < 2$ (see Fig. 33 of Pettini 2004).

2.3. Stellar Mass Density

The cosmic stellar mass density provides an integral constraint on the SFRD, $\rho_*(t) = \int_0^t d\rho_*/dt$. See Dickinson et al. (2003) for a recent compilation, and Niv Drory's contribution to this volume for an update. Note that the stellar masses of galaxies are not direct observables but are inferred from rest-frame optical (and near-infrared) photometry by modelling each object's star formation history using an assumed initial mass function (IMF).

2.4. Cosmic Metal Enrichment History

The cosmic metal density is really a history of cosmic metal enrichment due to star formation, $\rho_*(t) = 1/42 \int_0^t d\rho_*/dt$ (Pettini 2004). Wolfe et al. (2005, see their Fig. 7) show that the cosmic metallicity traced by DLAs rises gradually from a mean value of [M/H]=-1.5 at $z \simeq 4$ to a mean value of -0.7 at $z \simeq 1$. The range of observed DLA metallicities is somewhat higher than that of halo stars but overlaps, and is somewhat lower than that of thick disk stars and far lower than the near-solar values seen for thin disk stars in the Milky Way. The DLAs uniformly show greater metal enrichment than the Lyman α forest but less than values inferred for Lyman break galaxies or quasars at the same epoch (see Figs. 8, 32 of Pettini 2004, and see Leitherer 2005 for a review). The values given above are the cosmic mean metallicity of the neutral gas traced by DLAs, but they do not represent a full census of metals, which can also be found in heavily star-forming regions that have already used up their neutral gas or can be expelled by galactic winds into the IGM, which is predominantly ionized. It is therefore useful to compare the observed DLA metallicities with those expected from the DLA star formation rates; this leads to a factor of ten deficit in the observed metallicities called the "Missing Metals Problem" (Wolfe et al. 2005; Hopkins et al. 2005; Pettini 1999). The most likely explanation is that the star-forming regions of the galaxies seen as DLAs have superwinds sufficiently strong to move most of the metals produced into the IGM.

3. Theoretical Advances

Theoretical efforts to understand and model galaxy formation are mostly beyond the analytical realm, where they divide into semi-analytic models and cosmological simulations. These two approaches have been converging in recent years, as the practitioners of cosmological hydrodynamic simulations are using more detailed "recipes" for star formation, supernova feedback, and winds and in some cases have claimed grandiose results from purely N-body simulations with many semi-analytic recipes added (e.g. Springel et al. 2005). For examples of state-of-the-art cosmological hydrodynamic simulations of high-redshift galaxies and AGN, see Nagamine, Springel, & Hernquist (2004) and Di Matteo, Springel, & Hernquist (2005).

Semi-analytic models reproduce observations moderately well but have yet to demonstrate much success in predicting future observations, making them more of a tool for interpreting results than theoretical models in the classic sense. Somerville, Primack, & Faber (2001) tuned their models to reproduce galaxy properties at $z = 0$ and found one of their models to be in good agreement with the dust-corrected points at $z > 2$ in the cosmic SFRD diagram. However, as mentioned above, semi-analytic models for infall, merging, and winds are highly uncertain and it is not clear if observations of the cosmic density of neutral gas and the missing metals problem are consistent with the predictions. Similar scatter is seen in theoretical predictions of the cosmic stellar mass density.

4. Protogalaxy Demographics

DLAs dominate the neutral gas, making DLA-based studies appropriate for determining its cosmic density. However, other cosmological quantities should be summed over all high-redshift objects rather than just DLAs or just Lyman break galaxies, which trace the bright end of the high-redshift rest-UV galaxy luminosity function. Another motivation for studying all types of objects is the search for the progenitors of typical spiral galaxies like the Milky Way, which have not yet been pinpointed amongst the zoo of high-redshift galaxies. In designing the Multiwavelength Survey by Yale-Chile (MUSYC, Gawiser et al. 2005a, http://www.astro.yale.edu/MUSYC), it was decided to focus on selecting all known populations of galaxies at $z \simeq 3$, where most objects are young and several selection techniques overlap (see review by Stern & Spinrad 1999). The various populations at this epoch are labelled by three-letter acronyms (TLAs). We discuss each below.

4.1. Lyman Break Galaxies (LBGs)

The Lyman break galaxies (LBGs) are selected via the Lyman break at 912Å in the rest-frame. Higher-energy photons are unable to escape the galaxies or travel far in the IGM due to the large cross-section for absorption of ionizing photons by neutral hydrogen (for an illustration of the technique first successfully applied by Steidel & Hamilton 1992, see Fig. 19 of Pettini 2004). At $z \simeq 3$, the Lyman break generates a very red color in $U - V$, which could also be observed for an intrinsically red object such as an M dwarf or elliptical galaxy, leading to the additional requirement of a blue continuum color in e.g. $V - R$, consistent with the expected starburst nature of young galaxies. This makes the LBG technique insensitive to heavily dust-reddened or evolved stellar populations.

The selected population of galaxies is described in detail by Giavalisco (2002) and Steidel et al. (2003). Star formation rates range from 10-1000 $M_\odot$ yr^{-1} with a median value of ~ 50 $M_\odot$ yr^{-1} after correction for reddening values ranging over $0 \lesssim E(B-V) \lesssim 0.4$ (Pettini 2004). Inferred stellar masses range over $6\times10^8 M_\odot \lesssim M_* \lesssim 10^{11} M_\odot$ with median value $2\times10^{10} M_\odot$. Implied stellar ages range over 1 Myr$\lesssim t_* \lesssim 2$ Gyr with median age 500 Myr (Shapley et al. 2005). Observed qualities of LBGs are summarized in Tables 1 and 2 below, giving values for the space density, clustering length and dark matter halo masses from Adelberger et al. (2005), the SFR and stellar mass per object and stellar mass density from Shapley et al. (2001) and the cosmic SFRD from Steidel et al. (1999).

4.2. Lyman Alpha Emitters (LAEs)

Starbursting galaxies can emit most of their ultraviolet luminosity in the Lyman α line. Because Lyman α photons are resonantly scattered in neutral hydrogen, even a small amount of dust will quench this emission. Hence, selecting objects with strong Lyman α emission lines is expected to reveal a set of objects in the early phases of rapid star formation. These could either be young objects in their first burst of star formation or evolved galaxies undergoing a starburst due to a recent merger. Selecting galaxies with strong emission lines also allows us to probe the high-redshift luminosity function dimmer than the "spectroscopic" continuum limit of magnitude $R = 25.5$ that is used to select the Steidel et al. LBG samples, since continuum detection is not necessary for spectroscopic confirmation using the emission line.

Observed qualities of the Lyman Alpha Emitting galaxies (LAEs) are summarized in Tables 1 and 2 below, giving values for the SFR per object from Hu, Cowie, & McMahon (1998) and the space density, SFRD, clustering length and dark matter halo masses from MUSYC (Gawiser et al. 2005b).

4.3. Distant Red Galaxies (DRGs)

The inability of the Lyman break selection technique to find intrinsically red objects can be overcome by using observed NIR imaging to select high-redshift galaxies via their rest-frame Balmer/4000Å break. Looking for a continuum break in $J-K$ selects objects at $2 < z < 4$, labelled Distant Red Galaxies (DRGs) (Franx et al. 2003; van Dokkum et al. 2003). Reddy et al. (2005) offer a comparison of the redshift distributions of objects selected by LBG/star-forming colors, DRGs selected in $J-K$, and the passive evolution and star-forming samples selected through their BzK colors by Daddi et al. (2004). Note that this comparison is somewhat biased as the spectroscopic follow-up was performed on a sample originally selected only by the LBG/star-forming criteria. van Dokkum et al. (2005) report MUSYC results for an analogous comparison derived from a K-selected sample with inferred stellar masses $> 10^{11} M_\odot$.

Observed qualities of DRGs are summarized in Tables 1 and 2 below, giving values for the SFR and stellar mass per object from van Dokkum et al. (2004) and for the space density, SFRD, stellar mass density, clustering length and dark matter halo masses from MUSYC (Gawiser et al, in preparation).

4.4. Sub-Millimeter Galaxies (SMGs)

The Sub-millimeter galaxies (SMGs) are selected using sub-millimeter bolometer arrays, e.g. SCUBA or MAMBO, which have poor spatial resolution, $\sim 15''$. Complementary high-resolution radio imaging is needed to obtain positions accurate enough to find optical counterparts or perform spectroscopy. This means that the SMGs with redshifts are really jointly selected in both sub-mm and radio. Observed qualities of SMGs are summarized in Tables 1 and 2 below, giving values for the space density from Chapman et al. (2003), the SFR per object and SFR density from Chapman et al. (2005), the clustering length from Webb et al. (2003) and the dark matter halo masses from MUSYC (Gawiser et al., in preparation).

4.5. Damped Lyman α Absorption Systems (DLAs)

The Damped Lyman α Absorption systems (DLAs) were introduced above in §2.1. Observed qualities of DLAs are summarized in Tables 1 and 2 below, giving the range of SFR per object for the two DLAs for which this quantity has been determined (Møller et al. 2002; Bunker 2004, see Wolfe et al. 2005 for a review). Also shown are the SFR density from Wolfe et al. (2003a) and the clustering length and dark matter halo masses determined by Cooke et al. (2005).

5. Clustering of protogalaxies

It seems appropriate to provide a brief summary of the method used to generate the clustering lengths and inferred dark matter halo masses given in the Tables. The spatial correlation function $\xi(r) = (r/r_0)^{-\gamma}$ is inferred by fitting a power-law to either the observed spatial or angular correlation function of the sample. If only angular positions are observed, the redshift distribution $N(z)$ must be measured spectroscopically and used to invert the Limber equation as described in Giavalisco et al. (1998). The Landy-Szalay estimator is typically used to estimate the angular or spatial correlation function of the datapoints and to correct for the so-called "integral constraint" caused by measuring the mean density of the population from the observed survey volume (Landy & Szalay 1993). The LBG, LAE, and DRG samples are large enough to use the correlation length r_0 measured from the auto-correlation function to determine the bias factor e.g. b_{LBG}, following

$$\xi_{LBG-LBG}(r) = (r/r_0)^{-\gamma} = b_{LBG}^2 \xi_{DM}(r), \tag{2}$$

where $\xi_{DM}(r)$ is the dark matter autocorrelation function predicted by the ΛCDM cosmology. The SMG and DLA samples are small, so their cross-correlation with the more numerous LBGs is used to determine their bias factor, e.g.

$$\xi_{DLA-LBG}(r) = (r/r_0)^{-\gamma} = b_{DLA} b_{LBG} \xi_{DM}(r). \tag{3}$$

The bias factor of each family of protogalaxies determines its typical dark matter halo mass following the method of Mo & White (1996), whose application to the cross-correlation function was first suggested by Gawiser et al. (2001).

This method also allows one to predict the number abundance of dark matter halos with mass above the given threshold mass and to compare this with the observed number density of the population to infer the average halo occupation number.

Table 1. The $z = 3$ universe. References for entries are given in the text, with a few entries still to be determined from MUSYC, ALMA, and JWST. Typical systematic uncertainties are a factor of two.

TLA	Space density $[h_{70}^3\ \mathrm{Mpc}^{-3}]$	SFR per object $[\mathrm{M}_\odot \mathrm{yr}^{-1}]$	Stellar mass per object $[\mathrm{M}_\odot]$	Clustering length (r_0) $[\mathrm{h}_{70}^{-1}\ \mathrm{Mpc}]$
LBG	2×10^{-3}	30	10^{10}	6 ± 1
LAE	3×10^{-4}	6	MUSYC	4 ± 1
DRG	3×10^{-4}	200	2×10^{11}	9 ± 2
SMG	2×10^{-6}	1000	MUSYC	16 ± 7
DLA	ALMA	1–50	JWST	4 ± 2

Table 2. Cosmological quantities. References for entries are given in the text, with a few entries still to be determined from MUSYC and JWST. Typical systematic uncertainties are a factor of three.

TLA	SFR density $[\mathrm{M}_\odot \mathrm{yr}^{-1} h_{70}^3\ \mathrm{Mpc}^{-3}]$	Stellar mass density $[\mathrm{M}_\odot h_{70}^3\ \mathrm{Mpc}^{-3}]$	Dark matter halo mass $[\mathrm{M}_\odot]$
LBG	0.1	10^7	3×10^{11}
LAE	0.002	MUSYC	10^{11}
DRG	0.06	6×10^7	3×10^{12}
SMG	0.02	MUSYC	10^{13}
DLA	0.03	JWST	10^{11}

6. Five Unsolved Problems in Galaxy Formation

1. *What does a protogalaxy look like?* The term protogalaxy has been used loosely here and in the literature to describe young galaxies at high redshift. Part of the difficulty is that once an object has sufficient stars to be observed in rest-frame UV or optical radiation, we consider it a galaxy. But before this time it is either unobservable or only observable in absorption (e.g. DLAs), X-ray emission from a supermassive black hole (quasars/AGN), or in far-infrared radiation from dust which could be enshrouding either a powerful AGN or rapid star formation. If dark matter halo collapse, initial star formation and supermassive black hole formation all occur simultaneously, the formation epoch of the galaxy is well-defined, and the picture is simple. But it is possible that many collapsed halos remain quiescent clouds of neutral gas until star formation is triggered by

later mergers; these objects could comprise the half of DLAs that fail to show significant cooling in the [CII] 158 micron line (Wolfe et al. 2004). The distribution of lag times between dark matter halo collapse, supermassive black hole formation, and rapid star formation remain uncertain.

2. *When/how did each component of the Galaxy form?* Observations indicate that the thin disk formed at $z \simeq 2$, but simulations have trouble creating disk galaxies. One area now receiving attention is the manner in which angular momentum coupling between dark matter and baryons affects bar/disk formation and the cuspiness of bulges. It is still not clear if the globular clusters should be considered Galactic components or were all formed earlier and captured, despite evidence that some globular clusters are captured dwarf galaxies. Could globular clusters have formed in the same low-mass halos that met the Jeans threshold for collapse after recombination and hosted the Population III stars?

3. *When/how did galaxy sequences evolve?* HST observations of morphologies of galaxies at $z > 2$ imply that the Hubble sequence was not yet present. This is somewhat subtle, as cosmological surface brightness dimming would make a face-on spiral appear very different at high redshift, but most objects display irregular morphology and even the most promising edge-on disk candidates show spectroscopic kinematics inconsistent with the presence of disks (Erb et al. 2004). However, in the low-redshift ($z < 1$) universe we see a clear bimodality in the distribution of galaxy properties, the so-called red and blue sequences (e.g. Bell et al. 2004; Kannappan 2004). Such bimodalities are unlikely to arise from cosmological structure formation but are presumably caused by baryonic physics and appear directly linked to the "downsizing" behavior discussed in §1.1.

4. *What role did feedback play?* The non-linear baryonic physics of star formation leads to highly energetic processes (ultraviolet radiation, stellar winds, supernova explosions) that can ionize or expel neutral gas that would otherwise participate in further star formation. It is now clear that the processes of galaxy and supermassive black hole formation are intimately connected, as evidenced by striking correlations between the masses of black holes and the velocity dispersions (or masses) of bulges in which they are embedded (Gebhardt et al. 2000; Ferrarese & Merritt 2000; Kormendy & Richstone 1995; Magorrian et al. 1998). Possible explanations include simultaneous hierarchical growth of galaxies and their central black holes through mergers (Haehnelt & Kauffmann 2000; Di Matteo et al. 2005), a strong coupling between black hole accretion and star formation in proto-disks at high redshift (e.g. Burkert & Silk 2001), and the effects of AGN feedback on the surrounding intergalactic medium (Scannapieco, Silk, & Bouwens 2005). One way or another, it appears that feedback from AGN, supernovae, and galactic winds must regulate the joint formation of the bulge and central black hole. Feedback may also play a role in determining the cuspiness of the dark matter halos, which does not appear consistent with profiles predicted from N-body simulations (Silk 2004). The galactic winds play a critical role in metal enrichment of the intergalactic medium and probably play a lesser role in ejecting neutral gas from the galaxies. As mentioned above, supernova feedback may explain the apparent minimum galaxy mass.

5. *When/how was the universe reionized?* A major area of ongoing investigation is the reionization epoch when the intergalactic medium was ionized.

Slightly inconsistent results have been reported for the reionization redshift from WMAP observations of the temperature-E-mode cross-power-spectrum ($z_r = 20 \pm 9$, Bennett et al. 2003) and the apparent end of reionization where the neutral hydrogen fraction dropped to 0.01 as seen in SDSS quasar spectra at $z \simeq 6.3$ (Fan et al. 2002). It seems premature to hypothesize bimodal models of reionization where separate families of sources produce the "early" ionization seen by WMAP and the completion of reionization seen by SDSS. Nonetheless, it is unclear at present which sources reionized the universe, and the leading candidates are the first generation of zero-metallicity stars (Population III) and starbursting galaxies including LBGs and LAEs. The quasars have very hard, ionizing spectra but were not numerous enough to reionize the universe at $z > 6$; they appear to dominate HeII reionization at $z \sim 3$. Significant uncertainties exist regarding the nature of the Population III stars: did they form in $10^6 M_\odot$ dark matter halos that collapsed after recombination, or in larger galaxies later on? A top-heavy initial mass function (IMF) is presumed for Population III, but what was the exact mass range and nature of stellar death? Did multiple stars occur per halo, or did the death of the first very massive star prevent further star formation or cause sufficient metal enrichment to generate Population II stars?

7. Conclusions: Coming Attractions

The speakers have been asked to discuss major advances expected in the coming decade. For galaxy formation, I will go on record with three promising predictions and one slightly fascetious warning.

The coming years will see the unification of galaxy formation and evolution. Until very recently, galaxy formation was studied at $z > 2.5$ and galaxy evolution was studied at $z < 1$ and the period $1 < z < 2.5$ was referred to as the "redshift desert". But technological advances in NIR imaging and spectroscopy have made the rest-frame Balmer/4000Å break and nearby emission lines available for study in distant galaxies. Development of these "needle-in-a-haystack" techniques now allows us to successfully find evolved galaxies at $z > 2$ even though these objects may be rare at those epochs. Hence we are beginning to study objects at $z \sim 3$ that formed at $z > 6$ which may turn out to be much easier than observing $z > 6$ galaxies directly. Imaging with the Spitzer satellite is enabling the first studies of rest-frame near-infrared emission from $z > 2$ galaxies, breaking degeneracies between age and dust. Deep imaging and slitless spectroscopy with the GALEX satellite are revealing the analogs of Lyman break galaxies at low redshift (Burgarella et al. 2005). These combined studies may make it possible to piece together a rough evolutionary sequence, e.g. DLA→LAE→LBG→SMG→DRG, that would form part of a *grand unified* model of high-redshift galaxies and AGN.

We will be able to study the interstellar medium in emission at high-redshift. ALMA will enable studies of molecular gas in young galaxies through high-order CO lines. The [CII] 158 micron line, which dominates the cooling of the Cold Neutral Medium phase at both low and high redshift, should be detectable for galaxies with large gas mass or rapid cooling equilibrating the heating due to starbursts. The current set of Early Universe Molecular Emission Line Galaxies consist mostly of quasars and are reviewed (and assigned the questionable TLA "EMG") by Solomon & vanden Bout (2005). Both CO and [CII] have now been detected in $z > 6$ SDSS quasars, where they provide the best direct probes of the quasar host galaxies (Bertoldi et al. 2003; Walter et al. 2004; Maiolino et al. 2005). Detecting these lines and the sub-millimeter dust continuum from protogalaxies with ALMA will allow us to probe a multivariate mass function of gas mass, molecular mass, dust mass, and stellar mass. Even ALMA sensitivity may only allow detections of the tip of the gas-mass function, but this will provide a complementary set of objects to the tip of the rest-frame-UV and rest-frame-optical luminosity functions currently studied at high redshift, and much can be learned from the intersection and union of these samples.

High-redshift galaxies will be used to constrain dark energy properties. It has recently been shown (Seo & Eisenstein 2003; Linder 2003; Blake & Glazebrook 2003) that the scale of baryon acoustic oscillations provides a "standard rod" that can be measured in the clustering of high-redshift galaxies. The measurement will constrain the dark energy equation-of-state as a function of redshift, $w(z)$, via its influence on the expansion history of the universe. The measurement can be performed at any redshift where the line-of-sight starting at $z = 0$ is sufficiently influenced by the dark energy, making $z = 1$ and $z = 3$ equally acceptable. Of order a million redshifts are needed, and the most likely surveys to accomplish this ambitious goal appear to be HETDEX using the VIRUS instrument under construction for HET and the wide-field multi-fiber spectrograph KAOS proposed for Gemini.

The rapidly increasing sophistication of studies of the high-redshift universe will generate even more jargon. We are already debating proper nomenclature for special categories of DLAs at lower column density (sub-DLAs) and those found in gamma-ray burst afterglows (burst-DLAs or bDLAs). Four-letter object acronyms (FLOAs?) are going to be part of the future.

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