Studying Galaxy Formation with Hubble’s Successor

Rachel S. Somerville
Department of Astronomy, University of Michigan, Ann Arbor, MI 48109

Abstract. In this paper, I discuss the capabilities and limitations of an 8-10 m ultraviolet/optical telescope in space, the proposed successor to the Hubble Space Telescope, in the context of galaxy studies. The exquisite spatial resolution and excellent sensitivity of such a facility would open up new possibilities for the study of nearby dwarf galaxies ($z < 0.5$), and for studying the internal structure and kinematics of more luminous galaxies at high redshift ($z > 2$). These applications are of particular importance because they would address areas in which the popular Cold Dark Matter theory is in potential conflict with observations.

1. What Do We Need to Know About Galaxy Formation?

The “Cold Dark Matter” (CDM) or hierarchical paradigm of structure formation provides a useful framework for attempting to understand galaxies and cosmology. As the values of the cosmological parameters within this framework have become more and more tightly constrained by non-galaxy-based observations (like the cosmic microwave background and supernovae), most of the major uncertainties have to do with the messy “gastrophysics” that connects dark matter with the gas and stars that we can observe directly. Some of these issues include:

- **Cooling** — observations indicate that less of the gas in the Universe has cooled than is predicted by simulations. In particular, cooling in clusters seems to have been “shut off” by some unknown process.

- **Star formation** — what determines how efficiently a galaxy can turn cold gas into stars? How does this efficiency scale with redshift and galaxy properties? What is the physical basis of empirical scaling laws such as the “Kennicutt Law” (Kennicutt 1989; 1998), and are they universal? What factors determine the duration and efficiency of the bursts of star formation seen in interacting galaxies? Is the stellar initial mass function universal in space and time, and why does it have its observed shape?

- **Stellar feedback** — how does the energy from massive stars and supernovae affect the interstellar medium (ISM), intergalactic medium (IGM), and intracluster medium (ICM), and how does this impact future generations of stars? Is the main effect predominantly thermal or kinetic? How important are turbulence and large-scale galactic winds and outflows?
• **Heavy elements and dust** — how efficiently are metals expelled from the potential wells of galaxies? How did the ICM and IGM get so uniformly polluted with heavy elements? Is there a universal dust-to-metal ratio in all galaxies? What determines the degree of optical/ultraviolet extinction a galaxy experiences? Do the properties of dust in galaxies (composition, temperature, etc.) differ dramatically from one galaxy to another, or as a function of redshift?

While the observations obtained with the new generation of space-based facilities and the large number of 6-10 m-class ground-based telescopes now coming on line will doubtless bring us a much better understanding of many of these issues, I expect that even 10–15 years from now, some of them will not be completely put to rest. In the remainder of this paper, I focus on a few specific examples of observations that would utilize the unique capabilities of the proposed Hubble Space Telescope successor (the “Next HST” – NHST) to address important theoretical questions about galaxy formation.

### 2. What Could We Do with a 10 m Optical Telescope in Space?

At the risk of stating the obvious, I shall go through some of the capabilities and limitations of the proposed NHST facility for studying galaxies. The ultraviolet/optical wavelength sensitivity is optimal for studying objects with young stellar populations. There are many indicators of star-formation activity in this wavelength range, although they are suspect due to the uncertain effects of dust. Because of the large aperture and the location in space, NHST would have exquisite spatial resolution. Space-based observations also have lower background and so lower flux limits. This is useful for looking at high redshift or intrinsically faint and/or low surface brightness objects (a familiar lesson from HST). However, by \( z \approx 6 \), the Lyman break has redshifted into the I-band, so a purely optical telescope will not be useful for observing galaxies at \( z > 6 \) or so (but that is what NGST is for).

Quantitatively, what would the proposed parameters of NHST allow us to do? The following calculations were done assuming a flat geometry, \( \Omega_m = 0.3 \), \( \Omega_\Lambda = 0.7 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Figure 1 (left) shows the apparent magnitude (AB system) or flux of several representative objects placed at different redshifts (no k-correction or evolution). The top line represents a large spiral galaxy similar to the Milky Way \( (M_B = -20) \), the middle line represents a typical dIrr galaxy like the SMC \( (M_B = -16) \), and the bottom line represents a very faint dwarf galaxy such as Sculptor \( (M_B = -10) \). Assuming a flux limit on the order of a 0.5–1 nJy, which should be easily obtainable with NHST, we see that luminous \( L \approx L_\star \) galaxies will be easily visible out to \( z \approx 6 \). Even much fainter objects like the SMC (about three magnitudes below \( L_\star \)) will be visible to \( z \approx 2 \). Objects like the very faintest dwarf galaxies known in the Local Group (9–10 magnitudes below \( L_\star \)) will be very difficult to see at truly impressive redshifts — but they should be visible out to redshifts of \( z \approx 0.5–1 \), while currently these extremely tiny objects can only be studied very locally (mostly within the Local Group). Of course, surface brightness dimming will make these objects even more difficult to detect at large distances.
3. Dwarf Galaxies in the Nearby Universe

Dwarf galaxies have long presented a particular challenge to CDM. Most people are now familiar with the problem that CDM models tend to produce steep luminosity functions and too many low-luminosity galaxies (e.g., White & Frenk 1991; Kauffmann, White, & Guiderdoni 1993). It is usually assumed that this can be cured by invoking supernova (SN) feedback, but most models for SN feedback are currently quite ad hoc, and it is important to obtain better direct observational constraints on this process. This is one of the reasons that the study of nearby dwarf galaxies is so important.

Another form of this problem that has received a lot of attention recently is known as the “substructure problem”; virialized halos in high-resolution CDM simulations have large amounts of surviving substructure, from previous generations of dark matter halos that have merged to form a larger halo (Klypin et al. 1999; Moore et al. 1999). There are several hundreds of bound substructures with $V_c \gtrsim 20$ km s$^{-1}$ within Local Group sized halos in the simulations, at least an order of magnitude larger than the number of dwarf galaxies observed in the Local Group (at most around 40).
To solve these problems within the context of standard CDM, clearly we must invoke some mechanism to either destroy these small halos or to prevent them from collecting gas and from forming stars. Supernova feedback may help, but would have to be strongly differential, much more effective in small mass objects than in large mass ones, in order to solve this problem without making star formation too inefficient in larger mass galaxies. Another possibility is that the presence of a photoionizing background could suppress gas infall and cooling in very small halos ($V_c \lesssim 30$–50 km s$^{-1}$). A number of recent studies using semi-analytic methods (Somerville 2002; Benson et al. 2002; Bullock, Kravtsov & Weinberg 2001) concur in the conclusion that if this effect (sometimes known as “squelching”) is as efficient as suggested by recent hydrodynamic simulations, then it can probably cure the substructure problem in the Local Group.

If the “squelching” picture is correct, there are a number of observational consequences that should be tested. There have been several recent proposals for ways to probe the substructure mass function in other galaxies using gravitational lensing (e.g., Metcalf & Madau 2001; Moustakas & Metcalf 2002). We might expect that an additional consequence of this picture would be that some small galaxies, which formed before the Universe became reionized, would experience a burst of early star formation but then be “squelched” — these objects should then have uniformly old stellar populations. This seems to be in conflict with the star-formation histories derived for dwarf galaxies in the Local Group — however, theory predicts that the halos that can collapse before reionization should be predominantly found in cluster environments (Tully et al. 2002). Another implication of the squelching picture is that as one goes down the mass function of dark matter halos, the mass-to-light ratio of halos should greatly increase. Since squelching is expected to be a somewhat gradual and stochastic process, one might be able to find very faint, surviving dwarf galaxies which could be used as dynamical tracers of the density field. Indeed, several candidates for these “dwarf groups”, with mass-to-light ratios about five times larger than those of normal groups, have been identified (Tully et al. 2002). A direct probe of squelching could also be obtained by measuring a “baryonic Tully-Fisher relation” (or the analog for spheroidals) for extreme dwarf galaxies ($M_B \leq -10$).

4. Structure and Kinematics of Galactic Disks

Another potentially serious problem for CDM-based models is the set of issues surrounding the internal structure of disk galaxies. It is now well-known that the density profiles of dark matter halos formed in dissipationless CDM simulations are “cuspy” – i.e., they rise fairly steeply in the center, with a slope of about $r^{-1}$ (Navarro, Frenk, & White 1997 (NFW); Bullock et al. 2001; Power et al. 2002). It is difficult to reconcile the observed rotation curves of some dwarf and low surface brightness galaxies with these NFW halos, which seem to predict too much dark matter in the central part, leading to rotation curves that rise too abruptly. There is considerable disagreement, however, about whether there really is a problem or whether the discrepancies can be explained by selection effects or observational errors. All of the problematic objects are from a subclass of extremely late type, dwarf and/or low surface brightness (LSB) galaxies.
Figure 2.  

Left: Rotation curve of the Milky Way. Symbols represent observational data. Curves represent various components from the favored model of KZS02, as indicated on the figure. In this model, transfer of angular momentum from the baryons to the dark matter has flattened the dark matter “cusp” near the center of the halo.  

Right: Mass profile of the Milky Way, from pc to $\sim 100$ kpc scales. Symbols represent observational data from stellar kinematics (inner points), HI kinematics (intermediate points) and satellite velocities (outer point). Observational references are given in KZS02, from which both figures are reproduced.

Perhaps this population can be accounted for if they are formed within halos drawn from an extreme tail of low concentrations or flat inner profiles. In order to lay this debate to rest, we need high resolution kinematics for a statistically complete sample of galaxies, extending to very low luminosities and surface brightnesses. The existing samples are sparse because these tiny, faint objects are so difficult to detect, and even more difficult to obtain good spectra for. The resolution, sensitivity, and high S/N that could be obtained with NHST could provide the necessary breakthrough to determine whether this is indeed a “crisis” for CDM.

If there really is a problem, perhaps it can be solved by appealing to baryonic processes. It is generally argued that this is unlikely for the objects in question, which are clearly dark matter dominated in the center. To go this route, one must appeal to an event that occurred at an early stage, leaving no directly observable trace. For example, cusps could be destroyed by an early, intense burst of star formation which simultaneously drove all the gas out of the halo, perhaps combined with subsequent tidal heating (Gnedin & Zhao 2001; Dekel & Devor 2002). Weinberg & Katz (2002) proposed that a large and massive rotating bar in the high-redshift progenitors of present day galaxies could destroy the inner dark matter cusps. These solutions all involve events which should produce rather dramatic observational signatures but which must occur at high enough redshift that they are safe (for the moment) from direct confrontation with observations. Perhaps the best way to test these ideas is to look directly at the high redshifts where these processes are assumed to occur. NHST would be
very useful for studying the internal structure and dynamics of the progenitors of present day galaxies, which may provide constraints on these kinds of scenarios.

It has also been suggested that there may be too much dark matter in the centers of luminous galaxies, like our own Milky Way (e.g., Binney & Evans 2001). Klypin, Zhao, & Somerville (2002; KZS02) found, however, that if there is moderate transfer of angular momentum from the baryons to the dark matter (about a factor of two), the detailed inner structure and kinematics of the Milky Way and M31 can be understood within the context of NFW halos (see Figure 2). The analytic solution of KZS02 is reminiscent of the process seen by Weinberg & Katz (2002) in their simulations.

One of the main uncertainties in interpreting galaxy rotation curve data is due to the difficulty in connecting the virial mass of the dark matter halo (typically, a few hundred kpc for bright galaxies) with the observed rotation curves, which probe only about the inner tenth of the halo. Especially for luminous galaxies, the gravitational force of the baryons is expected to significantly modify the profile in the central parts, where the baryons comprise about half of the mass. For the unique case of the Milky Way, we can reconstruct the mass profile over a huge range of scales (see Figure 2) by using different dynamical tracers: stellar kinematics on small scales (pc), the H\textsc{i} rotation curve on intermediate scales (kpc), and satellite velocities on large scales (100 kpc). As shown in KZS02, these combined data produce very strong constraints on the distribution of baryons and dark matter in the Milky Way. NHST could be used to obtain very high resolution kinematic data for the central parts of galaxies, and kinematic tracers of the outermost reaches of the halos of galaxies such as satellite galaxies, planetary nebulae, or globular clusters. These data could be combined with CO rotation curves from the Atacama Large Millimeter Array (ALMA) to obtain very tight constraints on the distribution of mass out to the virial radii of galaxies. This will be invaluable in understanding the complex process of disk formation and what determines the surface density profile and rotation curve of spiral galaxies. Similar exercises may be done for early type galaxies.

5. High Redshift Galaxies: What Are They?

We now know of the existence of well over a thousand galaxies at \( z > 2 \). While this is an enormous achievement, in many respects we still do not know what these objects are. Are they disks or spheroids? Are their star-formation rates so much higher than present-day galaxies because they have been brightened by collisions, or because their disks have higher gas surface densities? Do they follow the same fundamental scaling relations as nearby galaxies? What objects in the lower redshift Universe are their descendants? Arguably, we will not really know what these objects are until we image them at considerably higher resolution, and ideally, obtain spatially resolved kinematic data for them. Combined with information on the gas distribution from ALMA, this could allow us to test whether empirical star-formation laws like the Kennicutt law (1989; 1998) are universal.

What kind of resolution would this require? Figure 3 shows the predictions of a CDM-based semi-analytic model of galaxy formation for the structural
properties of galaxies at $z \sim 3$. This model is similar to those described in Somerville & Primack (1999) and Somerville, Primack, & Faber (2001; SPF), but includes a more detailed model of disk formation within cosmological “NFW” halos, including the effects of adiabatic contraction of the baryons using an approach similar to the one described in Mo, Mao, & White (1998). The left panel of Figure 3 shows the disk scale length (in kpc) versus the $I_{814}$ magnitude (AB). A couple of things are worth noting. While the predicted sizes of the brighter objects are consistent with those measured for Lyman break galaxies in the Hubble Deep Field (see SPF), the models predict that these objects are only the tip of the iceberg; there is a large population of objects too small and too faint for HST to resolve. The right panel shows the Tully-Fisher relation for the same model galaxies at $z = 3$ (note that the quantity plotted is the observed frame I-band, corresponding to rest far-ultraviolet, so it is not surprising that there is a large scatter in this relation). Note the break in this relation at around $I_{814} > 28$, which is caused by the inclusion of “squelching” in the models.

6. Summary

I have suggested several applications of the proposed NHST 8-10 m ultraviolet/optical space telescope to the study of galaxies. A concise summary of these suggestions follows:

- Study stellar populations of dwarf galaxies (constrain their star-formation histories, and test “squelching” scenario).

- Look for “dwarf groups” with high mass-to-light ratios (the tail of the “squelched” population).

- Collect high resolution kinematic data for a complete sample of nearby galaxies, including dwarf and LSB galaxies (assess “cusp” crisis).
• Constrain the dark matter around galaxies on scales of \( \sim 100 \) kpc using satellite galaxies, planetary nebulae, and/or globular clusters as kinematic tracers (understand disk and spheroid formation).

• Obtain high resolution imaging and spatially resolved kinematics of \( z \gtrsim 2 \) galaxies.

• Obtain star-formation indicators and gas surface densities for a broad range of environments and redshifts, to study the universality of empirical star-formation scaling laws.

References

Benson, A.J., Frenk, C.S., Lacey, C.G., Baugh, C.M. & Cole, S. 2002, MNRAS, 333, 177
Binney, J., & Evans, W. 2001, MNRAS, 327, 27
Bullock, J.S., Kravtsov, A.V., & Weinberg, D.H. 2000, ApJ, 539, 517
Bullock, J.S., Kolatt, T.S., Sigad, Y., Somerville, R.S., Kravtsov, A.V., Klypin, A., Primack, J.P., Dekel, A. 2001, MNRAS, 321, 559
Dekel, A., & Devor, J., 2002, preprint, astro-ph/0204452
Gnedin, O.Y., & Zhao, H.S. 2002, MNRAS, 333, 299
Kauffmann, G., White, S.D.M., & Guiderdoni, B., 1993, MNRAS, 264, 201
Kennicutt, R.C. 1989, ApJ, 344, 685
Kennicutt, R.C. 1998, ApJ, 498, 541
Klypin, A.A., Zhao, H.S., & Somerville, R.S. 2002, ApJ in press, astro-ph/0110390
Klypin, A.A., Kravtsov, A.V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Metcalf, R.B., & Madau, P. 2001, ApJ, 563, 9
Mo, H.J., Mao, S., & White, S.D.M. 1998, MNRAS, 295, 319
Moore, B., Ghigna, F., Governato, F., Lake, G., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Moustakas, L.A., & Metcalf, R.B., preprint, astro-ph/0206176
Navarro, J.F., Frenk, C.S., & White, S.D.M. 1997, ApJ 490, 493
Power, C., Navarro, J.F., Jenkins, A., Frenk, C.S., White, S.D.M., Springel, V., Stadel, J., Quinn, T. 2002, preprint, astro-ph/0201544
Somerville, R.S. 2002, ApJ, 572L, 23
Somerville, R.S., & Primack, J.R. 1999, MNRAS, 310, 1087
Somerville, R.S., Primack, J.R. & Faber, S.M. 2001, MNRAS, 320, 504
Tully, R.B., Somerville, R.S., Trentham, N., Verheijen, M.A.W. 2002, ApJ, 569, 573
Weinberg, M.D., & Katz, N. 2002, preprint, astro-ph/0110632
White, S.D.M., & Frenk, C.S. 1991, ApJ, 379, 52