

# BUILDING GALAXIES

The unprecedented accuracy of recent observations of the power spectrum of the cosmic microwave background leaves little doubt that the universe formed in a “hot big bang”, later cooling and condensing to form the stars and galaxies we observe today. However, the processes involved in galaxy formation and evolution are complex. Because the history of an individual galaxy cannot be observed directly, progress is possible only by combining the statistical evidence from direct observations of evolving galaxies with fossil evidence from the Milky Way and the local universe, detailed studies of the physical processes that govern galaxy evolution, and theoretical models.

Motivated by models of the collapse of matter in the universe, the hierarchical assembly theory provides an indispensable framework for studying the formation and evolution of galaxies. In this assembly picture, galaxies are built through the smooth accretion of gas and the merging of smaller units. Many empirical arguments lend support to this theory, including measurements of the build-up of stellar mass with cosmic time and direct observations of present-day galaxies accreting mass through mergers. Central questions about this process remain, however, and can be broadly summarized as follows:

## Question 1: **When and where did the stars form?**

The epochs and luminosity scales at which the assembly takes place are crucial elements of galaxy evolution. What sizes are galaxies when most of their stars form? Do substantial amounts of stars form during the merging process?

## Question 2: **When and where did the elements form and where did they go?**

The formation of the elements is a fundamental question closely related to the question of when and where the stars form. The formation and distribution of the heavy elements in stars depends on the physical properties of the stars and the medium that surrounds them. When in the history of the universe did these elements form? How were they dispersed throughout and between the galaxies?

## **I. The State of Galaxy Evolution in 2015.**

In the coming decade, an array of 8 to 10-meter class optical and infrared telescopes, satellites, and ground based sub-millimeter, millimeter and radio telescopes will allow remarkable progress on the problem of galaxy evolution. These facilities will enable an understanding of the pace of galaxy formation and the distribution of the elements both very locally and in the distant universe. In particular, we will know: (1) the composition of the Milky Way and its closest (dwarf) companions, (2) the broad star formation histories and properties of local galaxies, (3) the basic star-forming properties of typical galaxies as far back as 7 billion years in the history of the universe, (4) the basic star-forming properties of the most luminous galaxies up to 12 billion years ago, and (5) the existence of at least some galaxies 12.5 to 14 billion years ago. However, a detailed

understanding of the physical processes that govern the formation of typical galaxies awaits the next generation of facilities.

The James Webb Space Telescope (JWST), set to launch in 2011, will have substantially greater broad-band sensitivity than existing facilities in the near and mid-infrared. This facility will produce remarkable images of even intrinsically faint galaxies in the distant universe. However, the capabilities of JWST will not include higher-resolution spectroscopy or optical sensitivity ( $> 0.5\mu\text{m}$ ), but only moderate resolution spectroscopy ( $R = 1000$ ) over a relatively small field ( $3.4 \times 3.4$  arcminutes). In addition, the spatial resolution of JWST will limit its photometry in the crowded stellar fields of external galaxies. Thus, measurements of many of the important properties of both local and high-redshift galaxies, including stellar ages, kinematics, and detailed elemental abundances, require a separate facility. Nor will JWST have the flexibility to adjust its instrumentation to the needs of galaxy evolution in 2015.

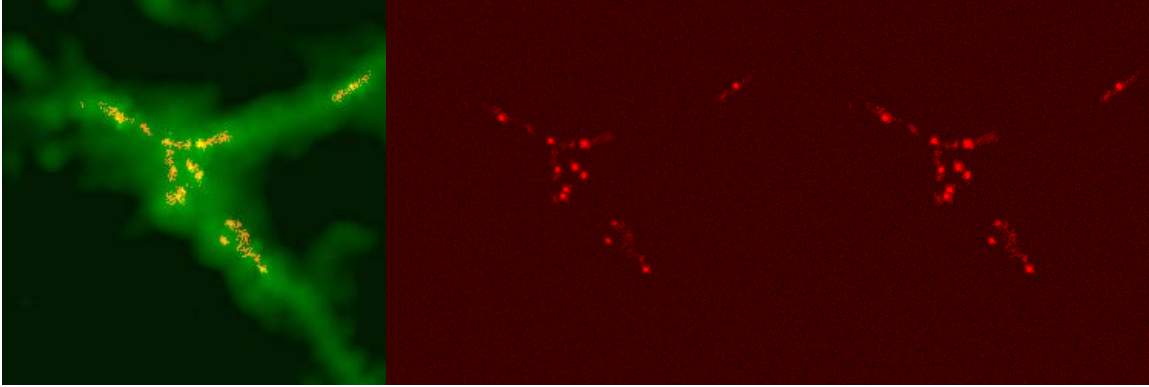
A large ground-based telescope with good corrected image quality and extensive capabilities at optical, near-infrared, mid- and possibly far-infrared wavelengths would be poised to address many of the most pressing and fundamental issues in galaxy evolution. Below, we outline several specific scientific capabilities a large, ground-based telescope might have to significantly advance our knowledge of galaxy evolution.

**II. The "fossil" remains of star and element formation.** (Placeholder for Mike and Knut.) The knowledge of the star formation and enrichment histories of "fossil" galaxies gives us a starting point for looking directly into the early universe to see the stars forming.

**III. The intergalactic medium.** Where is the fuel for star formation in the universe? How is this intergalactic medium affected by the formation of stars? (Placeholder for Jill.)

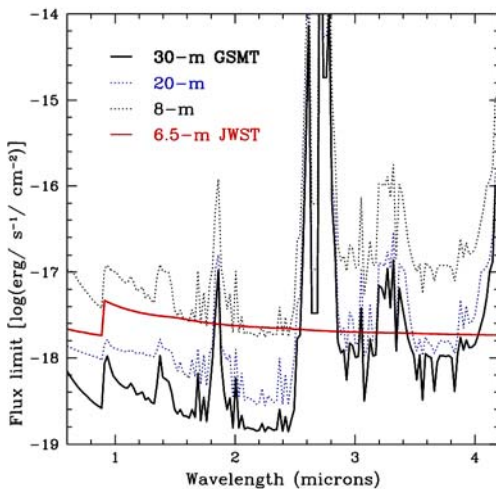
**IV. Star formation from line emission in the very early universe.** When did the earliest stars form?

Hierarchical models of galaxy formation and assembly predict that some stars form very early, from gas that has no heavy metals. Emission-line flux from forming stars will be detectable at near-infrared wavelengths. Figure 1a illustrates a simulation of the early universe, from Davé, Katz, & Weinberg (2003), where the star formation rate and gas cooling rate have been converted to a flux in the Ly $\alpha$  emission line ( $\lambda 1216 \text{ \AA}$ ). In Figure 1b, we simulate a narrow-band observation of this flux with a 30-meter telescope at an observed wavelength of  $1.34\mu\text{m}$ ; the star-forming regions are clearly detectable. In addition, spectra or narrow-band images of other lines can provide a diagnostic of the stellar masses of the first stars. In Figure 1c, we simulate an observation of flux from a HeII line at  $\lambda 1640 \text{ \AA}$ ; the strength of this line is directly related to the hardness of the radiation field in the star-forming regions, and thus to the distribution of masses of the forming stars.



**Figure 1 .** The “first” stars in a forming galaxy from a hydrodynamical simulation by Davé, Katz, & Weinberg. The first image (*left*) of the newly forming universe 500 million years after the Big Bang ( $z=10$ ) shows the predicted line radiation ( $\text{Ly}\alpha$ ) from the cooling of clouds of gas that will eventually condense to form stars (*green*) and from the newly forming stars themselves (*yellow, red*). The second image (*middle*) depicts this emission from Hydrogen in the  $\text{Ly}\alpha$  line ( $\lambda 1216 \text{ \AA}$ ) through a 30-meter ground-based telescope at moderate resolution ( $R=3000$ ), and the third image (*right*) shows the strong emission from Helium ( $\text{HeII } \lambda 1640 \text{ \AA}$ ) that may be emitted by the first stars if they are extremely massive. (*Grateful acknowledgements to Romeel Davé and J.-D. Smith.*)

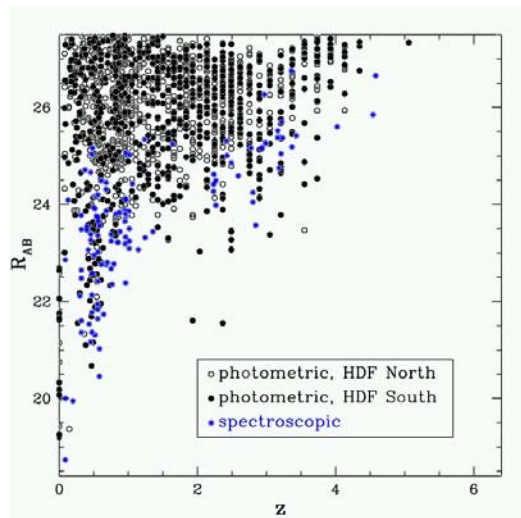
While JWST will detect these stars forming, a GSMT with good spectral resolving power and sensitivity will characterize the properties of these objects from measurements of the strengths of spectral lines, enabling a measurement of the amounts and types of stars that were formed, as well as an understanding of the opacity of these systems from the detailed profiles of the emission lines. Figure 2 shows the sensitivity of a GSMT to emission-line flux at a moderate resolution ( $R=3000$ ); in general, the sensitivity from the ground improves as the resolution increases.



**Figure 2.** The sensitivity of ground-based telescopes to emission line flux at a resolution  $R=3000$  in  $10^4$  seconds. We assume a collecting area of  $25\text{m}^2$  for JWST and collecting areas of 90% of the full aperture for the ground-based telescopes.

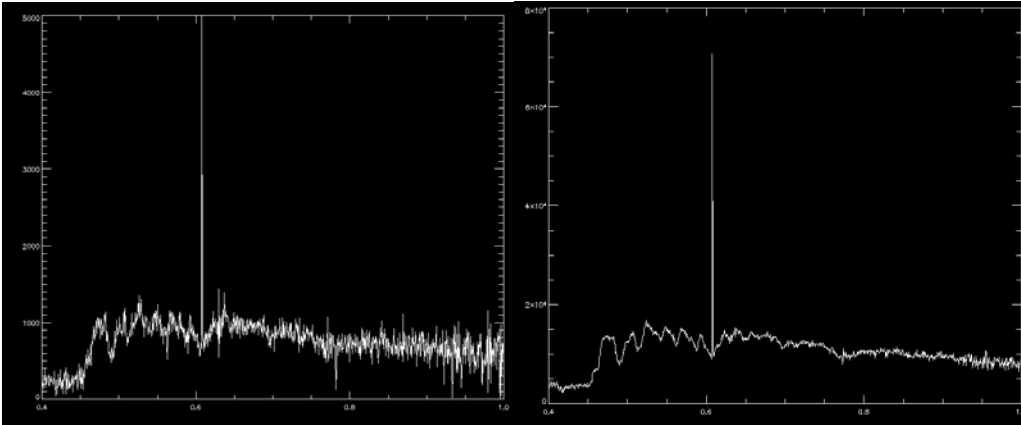
## V. A deep spectroscopic survey down the luminosity function. When did most of the stars form?

Existing facilities allow redshift measurements of the most luminous star-forming galaxies in the distant ( $z > 3$ ) universe, the “Lyman break” galaxies (Steidel et al. 1996). A telescope with much greater spectroscopic sensitivity than existing facilities will advance our knowledge of the galactic composition of the universe in two crucial ways. First, the “typical” galaxy in the early universe is not an extremely luminous system; lower-luminosity galaxies are important sites of star formation in the early universe. These systems may have merged to form many of the more luminous systems around today. Thus, an understanding of the majority of the galaxies in the universe requires a census of the luminosities, spatial distribution, and basic properties of the less luminous galaxies. Figure 4 illustrates the galaxy population available to a large, ground-based telescope. If coupled with the far-IR observations of reprocessed starlight, these data would provide, among other things, a complete census of the star formation in the local universe as a function of galaxy type (luminosity, redshift, metallicity, morphology).

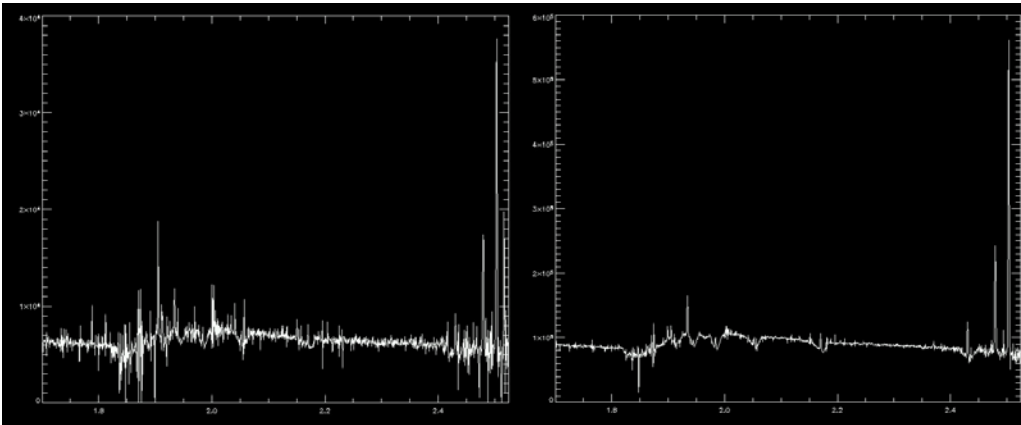


**Figure 4.** The population of high-redshift galaxies available to a GSMT. We show galaxies with photometric and spectroscopic redshifts in the Hubble Deep Fields. The arrows show the spectroscopic limits of ground-based 8-meter, 20-meter, and 30-meter telescopes at a resolution  $R=2000$  for a continuum  $S/N=3$  in  $10^4$  seconds, assuming 0.3 arcsecond seeing.

The second major contribution a GSMT would be poised to make to a large redshift survey is a dramatic improvement in the quality of rest-frame ultraviolet and near-infrared spectra. The information contained in these spectra would yield constraints on the metallicities and stellar initial mass functions of high-redshift galaxies. At present, extremely high-quality spectra are available for only one galaxy at  $z > 3$ , cB58, which is magnified by a factor of 30 by a gravitational lens. A GSMT would open up a world of new information about the properties of luminous star-forming galaxies in the high-redshift universe, allowing routine spectra with the quality of the cB58 observations. Figure 5 illustrates the difference in quality of spectra from 8-meter and 30-meter ground-based telescopes; Figure 6 shows similar comparison of near-infrared spectra (rest-frame optical).



**Figure 5.** Simulated rest-frame ultraviolet spectra of a  $z=4$  “Lyman break” galaxy with  $R_{AB}=24.5$ , through 8-meter (left) and 30-meter (right) ground-based telescopes in  $10^4$  seconds.



**Figure 6.** Simulated rest-frame optical spectra of a  $z=4$  “Lyman break” galaxy with  $K_{AB}=21.5$ , through 8-meter (left) and 30-meter (right) ground-based telescopes in  $10^4$  seconds.

## VI. Physical properties of high-redshift galaxies. Where did the stars form?

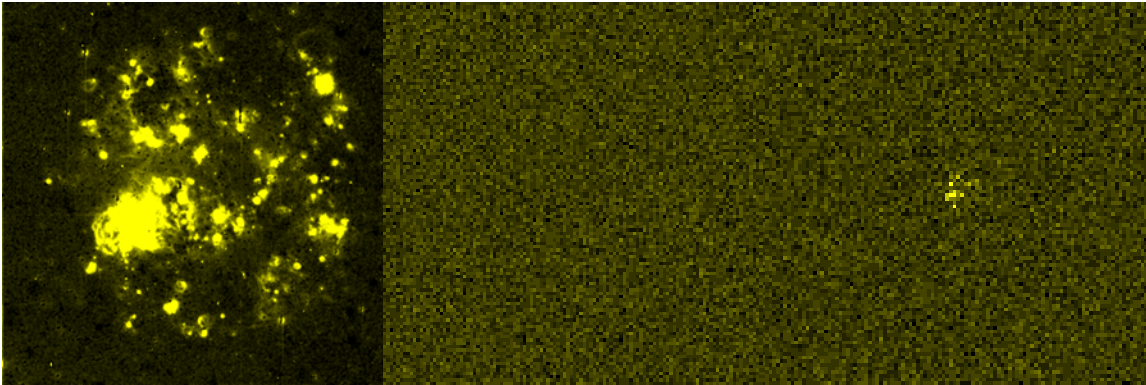
One of the most pressing questions in galaxy evolution is: what is the nature of the star-forming objects in the early universe? Currently, we have few clues about the *intrinsic* properties of the distant objects we observe. What will the objects we observe at high redshift evolve into at by the present day? Unique among existing or planned facilities, GSMT will allow measurements of the kinematic masses of high-redshift galaxies.

Figure 7 illustrates the abilities of ground-based telescopes to detect rest-frame optical emission lines from individual regions of strong star formation within a galaxy. The current class of 8 to 10-meter telescopes cannot measure spatially resolved spectra of star forming galaxies to redshifts much beyond  $z=1$ ; thus, these telescopes are unable to probe the epoch at which most of the stars in the universe formed. JWST will carry no instruments with sufficient spectroscopic resolution to measure the internal kinematics of high-redshift galaxies. A sensitive GSMT will detect regions of high star formation rate

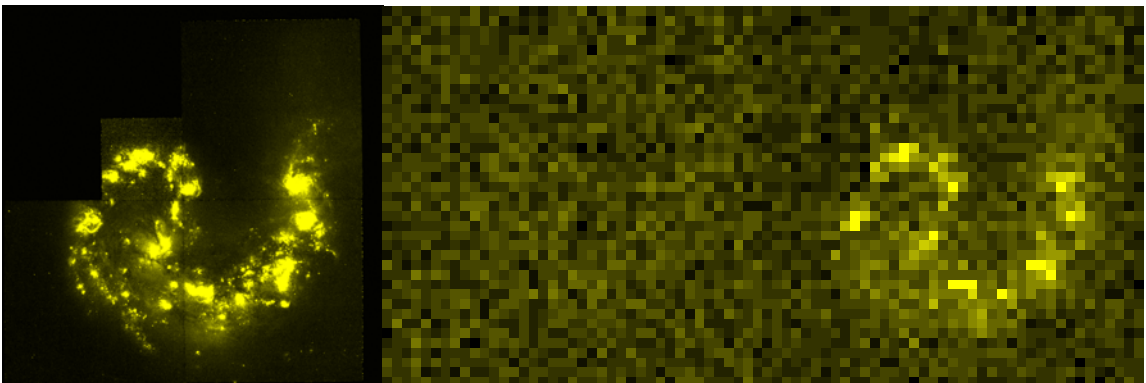
to redshifts as high as  $z \sim 5$  (Figure 8). Although high-redshift galaxies have very irregular structures, the measurements of internal motions within these galaxies will provide important constraints on the masses of their dark matter halos. These measurements will also enable us to distinguish between collapsing galaxies, dynamically “hot” collapsed systems, and the rotational motions of forming disks. Emission-line fluxes and flux ratios in the rest-frame optical also allow measurements of star formation rate and metal enrichment as a function of position within these assembling or assembled galaxies.

## VII. Summary.

A GSMT with a range of capabilities including sensitivity in the optical and infrared, good image quality, and a wide-field survey mode, will enable major breakthroughs in understanding of galaxy evolution, from the "fossil" evidence in nearby galaxies, through the star formation and metal enrichment history of the universe, to the physical processes which led directly to the assembly of galaxies.



**Figure 7.** Narrow-band images of the Large Magellanic Cloud. We show an  $H\alpha$  image of the LMC (*left*), along with simulated  $10^5$ -second narrow-band ( $R=3000$ ) images in the  $[OII](\lambda 3727 \text{ \AA})$  emission line at  $z=2.19$  through a ground-based 8-meter (*middle*) and a 30-meter telescope (*right*). The most luminous star-forming region in the Local Group, 30 Dor, is clearly detectable at high redshift. (*Image courtesy of R. Kennicutt.*)



**Figure 8.** Narrow-band images of the Antennae, a rigorously star-forming merger in the local universe. We show an HST/WFPC2  $H\alpha$  image of the Antennae (*left*), along with simulated  $10^5$ -second narrow-band ( $R=3000$ ) images in the  $[OII](\lambda 3727 \text{ \AA})$  emission line at  $z=4.715$  through a ground-based 8-meter telescope (*middle*) and a 30-meter telescope (*right*). A large optical telescope with good image quality will allow measurements of the internal kinematics and metallicities of star-forming regions at extremely high redshifts. (*Image courtesy of B. Whitmore.*)