Galaxies Across Cosmic Time with JWST

February 13, 2009

by Rogier A. Windhorst[1]

and the JWST Flight Science Working Group: John Mather (NASA/GSFC, chair), Mark Clampin (NASA/GSFC), Rene Doyon (U. of Montreal), Kathy Flanagan (STScI), Marijn Franx (Leiden U.), Jonathan Gardner (NASA/GSFC), Matthew Greenhouse (NASA/GSFC), Heidi Hammel (SSI), John Hutchings (Herzberg I. of A.), Peter Jakobsen (ESA), Simon Lilly (ETH-Zurich), Mark McCaughrean (U. of Exeter), Matt Mountain (STScI), George Rieke (U. of Arizona), George Sonneborn (NASA/GSFC), Massimo Stiavelli (STScI), and Gillian Wright (UK ATC).

Submitted to the 2010 Astronomy & Astrophysics Decadal Survey

[1] School of Earth & Space Exploration, Arizona State University, Box 871404, Tempe, AZ 85287-1404, USA; Email: Rogier.Windhorst@asu.edu

1. Introduction: The Four Big Questions that JWST will address in Galaxy Assembly

The James Webb Space Telescope (JWST; Gardner et al. 2006) will be a large, cold, infrared-optimized space telescope designed to enable fundamental breakthroughs in our understanding of the formation and evolution of galaxies, stars, and planetary systems (see Astro 2010 white papers by Gardner et al., Stiavelli et al., Meixner et al., G. Rieke et al., & Sonneborn et al.). In the current white paper, we describe the great potential of JWST in the theme of Galaxy Assembly.

Theory predicts that galaxies are assembled through a process of the hierarchical merging of dark matter concentrations (e.g., White & Frenk 1991; Cole et al. 1994). Small objects formed first, and were drawn together to form larger ones. This dynamical build-up of massive systems is accompanied by chemical evolution, as the gas (and dust) within the galaxies are processed through successive generations of stars. The interaction of these luminous components with the invisible dark matter produces the diverse properties of present-day galaxies, organized into the Hubble Sequence of galaxies. This galaxy assembly process is still occurring today, as the Magellanic Clouds fall into the Milky Way, and as the Andromeda Nebula heads toward the Milky Way for a possible future collision. To date, galaxies have been observed back to times about one billion years after the Big Bang. While most of these early galaxies are smaller and more irregular than present-day galaxies, some early galaxies are very similar to those seen nearby today.

The ΛCDM cold dark matter cosmological model provides a conceptual framework to understand the formation of galaxies through the hierarchical assembly of progressively more massive objects. However, many of the most basic questions about this process remain unanswered due to the difficulty of observing faint objects at high redshifts. The origins of the most fundamental scaling relations for galaxies is not well understood, and the CDM paradigm has not yet been well tested on galactic scales. "Semi-analytic" models for galaxy formation and evolution include many free parameters, while numerical gravitational/hydrodynamical simulations do not yet have the resolution and dynamic range to simultaneously model individual star-formation events and the growth of a galaxy in its cosmological environment. Hence, the formation and early evolution of galaxies is a complex and multifaceted problem that no single observation or theory will solve.

Despite all the work done to date, many questions remain open. We do not really know how galaxies formed, what controls their shapes, and what makes them form stars. We do not know how the chemical elements are generated and redistributed through the galaxies, and whether the central black holes exert great influence over the galaxy formation process. We do not know the global effects of violent events as small and large parts join together in collisions. JWST will be essential to address several key questions in the theme of galaxy Assembly, which include:

• **(1) When and how did the Hubble Sequence form?** The fundamental physics of the early universe determined the origin of the density fluctuations, their precise evolution with cosmic time, the nature of the Dark Matter and of Dark Energy. Each of these had a specific impact on the process of Galaxy Assembly, determining the hierarchical assembly of matter through gravitational instability over cosmic time.

• **(2) How did the heavy elements form during galaxy assembly?** How were the heavy elements exchanged between galaxies and their surrounding baryon reservoir? How did chemical enrichment evolve with cosmic time and galaxy environment?

• **(3) What physical processes determine galaxy properties?** How did star-formation proceed under a wide range of conditions, including those quite different from today? How did the feedback of energy and radiation produced by the first galaxies or pre-galactic objects impact the surrounding material, including the subsequent formation of (dwarf) galaxies and the reionization of the intergalactic medium.

• **(4) What are the roles of starbursts and black holes during galaxy assembly?** How did (super)massive black holes (SMBH's) originate and grow in the centers of galaxies, in particular ultra-luminous infrared galaxies (ULIRGs) and active galactic nuclei (AGN)? What powers these energetic extremely sources, especially at the highest redshifts?

Significant progress requires these new JWST data, both to characterize the galaxy population at different cosmic epochs, and to understand the astrophysics of key processes that are occurring in the universe at early times. To answer the most pressing of these questions, JWST will observe galaxies back to their earliest precursors, so that we can understand their growth and evolution. JWST will conduct deep-wide imaging and spectroscopic surveys of thousands of galaxies to study morphology, composition and the effects of environment. A host of observational issues must be understood, including point-source and surface-brightness sensitivity, the observational selection effects in wavelength, and the effects from dust obscuration. *Table 1 and §3 summarize how JWST will carry out the required observations for each of the four Galaxy Assembly focus themes.*

To gain deeper understanding of the very distant universe requires a systematic and comprehensive approach. Objects must be detected and identified by JWST (i.e., recognized as being at high redshift). Next, objects must be characterized by their physical properties and the physical processes occurring around them. They must be placed in the context of a global understanding of other objects and phenomena at the same epoch. It is also essential to understand which objects at one epoch evolve into which objects at a subsequent epoch, and to understand the relationship at all times between the visible baryonic material and the underlying dark matter.

2. The Assembly of Galaxies

2.0. Synopsis of Previous Investigations of Galaxy Assembly

During the mid-1990s, the simultaneous use of efficient multi-object spectrographs on large telescopes, the first 8 to 10 m telescopes and HST observations led to a dramatic advance in our direct observational knowledge of the galaxy population at earlier epochs. At $z \simeq 1$, the universe appears roughly similar at optical and near-infrared wavelengths to that seen today. There is a full range of Hubble types including spirals and ellipticals (e.g., Driver et al. 1995; Schade et al. 1995; Abraham et al. 1996; Brinchmann et al. 1998), a well-developed luminosity function of quiescent red galaxies (Lilly et al. 1995), approximately the same number density of large spiral disks, "normal" Tully-Fisher rotation curves in these disks (Vogt et al. 1996; 1997), and so on. The metallicities of the star-forming gas are close to solar. Some clear evolutionary effects are apparent, as luminous galaxies at $z \simeq 1$ have signatures of vigorous star-formation activity, such as blue colors, strong emission lines, irregular morphologies (Fig. 1). These indications are usually seen locally only in smaller galaxies, the so-called "down-sizing" effect (Cowie et al. 1995). In addition, the overall luminosity density in the ultraviolet, and in emission lines, is about 5× higher at $z \simeq 1$ than it is locally.

Extending beyond $z \simeq 1$, the known galaxies at $z \simeq 3$ are generally blue with compact or irregular morphologies. Most of these galaxies have been selected in the ultraviolet, and it is not yet clear whether there is a real absence of well-developed spiral or quiescent elliptical galaxies at this redshift. Nor is it clear when such galaxies first appear (see e.g., Giavalisco et al. 1996, Driver et al. 1998, Abraham et al. 1999, Zepf 1997, Dickinson 2000, Franx et al. 2003). Recent Spitzer results have begun to address this question by examining the population at $z \simeq 2$ (Yan et al. 2004; Labbé et al.

2005). Some galaxies appear to have substantial old stellar populations by z$\simeq$3, but there does not seem to be a large, previously hidden population of old galaxies (Barmby et al. 2004). Spitzer 24 μm detections of extremely red galaxies at z$\simeq$2 show two populations, merger-induced dusty starbursts and galaxies with old stellar populations (Yan et al. 2005; Chary et al. 2004).

The first samples selected through deep K-band imaging appear to show large numbers of red galaxies at redshifts approaching z$\simeq$2 (McCarthy et al. 2004, Abraham et al. 2004), although their stellar masses are sufficiently uncertain that it is not yet clear what fraction of the z$\simeq$1 population these represent. Ultraviolet-selected galaxies studied in detail at z$\simeq$3 show evidence for significantly sub-solar metallicities (z$\simeq$0.3 $Z_\odot$) and for galactic winds of several hundred km s^{-1}, indicating substantial ejection of enriched material into the intergalactic medium (Steidel et al. 1999).

Beyond z$\simeq$3, our picture of the galaxy population becomes very fragmentary as we approach the epoch at which reionization has been completed (z$\simeq$6–7). Samples of high redshift galaxies have been found through their strong Lyα emission (Hu et al. 2002, 2004; Rhoads et al. 2003) or by extensions of the Lyman break "drop-out" technique to longer wavelengths (Dickinson et al. 2004, Bouwens et al. 2003, Yan & Windhorst 2004b), but systematic and detailed study of these exceedingly faint objects is difficult and relies on the bright-end of the luminosity function (e.g., Bouwens et al. 2005). It is clear that the redshift range 1 z$\lesssim$z$\lesssim$7 is when the galaxy population acquired most of its present-day characteristics, when a large fraction of the stars we see today were formed, and when a large fraction of the metals was produced. Accordingly, this is the period when the most important astrophysical processes in galaxy formation and evolution occurred.

2.a. Focus 1: When and How Did the Hubble Sequence Form?

Some of main questions that JWST will address are: • Where were stars in the Hubble Sequence galaxies formed? • When did luminous quiescent galaxies appear? • How does this depend on the environment? • (How) did the epoch dependent merger rate drive galaxy assembly?

To answer these questions, we need JWST observations of the morphologies, stellar populations, and star-formation rates in a very large sample of galaxies observed in deep imaging and spectroscopic surveys. This investigation has substantial overlap with the chemical enrichment of galaxies, the measurement of masses, and the nature of the highly obscured luminous galaxies. JWST will characterize the star-formation rates in individual galaxies, as a function of their mass, environment, and cosmic epoch. JWST will also determine when the long-lived stars in a typical galaxy were formed, whether *in situ* or in smaller galaxies that subsequently merged together to form a large galaxy. Direct characterization of the merging rate of galaxies will provide another angle on this question.

The emergence of quiescent red galaxies, which have completed their major episodes of star formation, at least for the time being, will tell us why star formation ceases in some galaxies. The importance of chaotic star formation in starbursts, as compared with the steady-state star formation in stable galactic disks, will reveal the modes of star formation that dominate different phases of galactic evolution, and that develop the morphological components in the galaxies. Quantities such as the disk-size function, as well as color gradients within galactic disks at different redshifts will show directly how galactic disks grew, while the merger rate of disk galaxies will reveal the rate at which stars, originally formed in disks, are redistributed into the spheroids. Only with JWST can the relationship between old and young stellar populations be understood fully, and only with JWST can a full characterization of the star-formation process at high redshift be made.

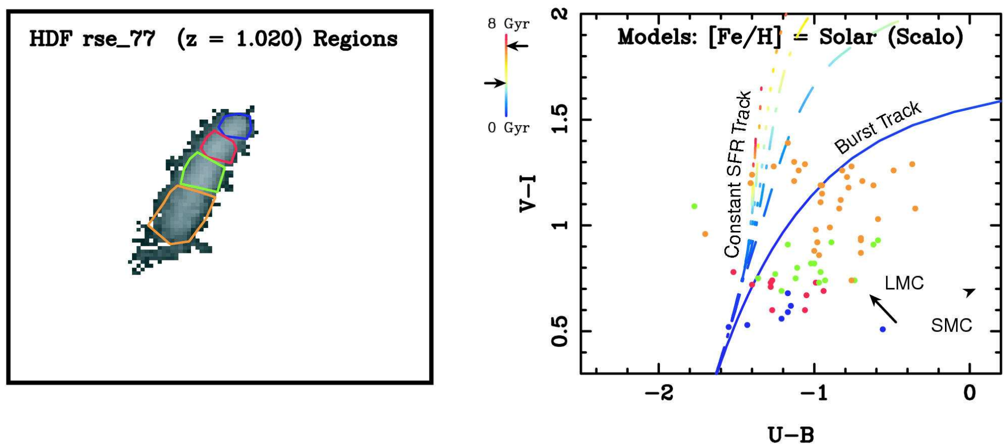


Fig. 1: Galaxies in deep HST images are separated on the basis of color into regions with different star-formation histories. The LEFT panels shows four different color regions in the galaxy image. In the RIGHT panel, these regions are placed pixel-by-pixel on a color-color diagram and compared to model predictions to determine the ages of the regions. The arrows labeled LMC and SMC are reddening curves from the Large & Small Magellanic Clouds, respectively (from Abraham et al. 1997).

2.b. Focus 2: How did the Heavy Elements Form during Galaxy Assembly?

Some of main questions here are: • Where and when are the heavy elements produced? • How and to what extent do galaxies exchange material with the intergalactic medium?

The average metallicity of the universe and of the objects in it as a function of epoch provides a fundamental metric reflecting the development of structure and complexity on galactic scales. Metallicity is observable and "long-lived" in the sense that heavy atomic nuclei, once produced, are not readily destroyed. The production of heavy elements is also one of only two cosmologically significant producers of luminosity in the universe, along with gravitational accretion energy.

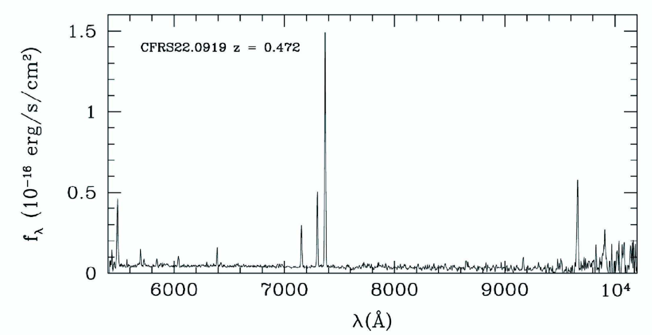
For many years, the metallicities of gas at high redshifts have been studied through the analysis of absorption line systems seen in quasar spectra (e.g., Hamann & Ferland 1999). The lines of sight to quasars probe random regions of the universe. The study of the metallicities of material in galaxies at high redshift is at a much earlier stage of development. This is more relevant for models of the chemical evolution of galaxies and for the use of metallicity estimates to constrain the present-day descendants of high redshift galaxies. The emission-line gas in star-forming regions is relevant for planetary and astro-biological studies, since it is likely to be representative of the material out of which the stars and planets are made.

Metallicities will be determined for $1.7 \lesssim z \lesssim 7$ to tie in with the observations of "first light" and the very first enrichment, and to trace the development of metallicity through the epoch when most of the stars and metals were made. Measurement of the gas metallicity in a very large number of faint galaxies (i.e., the metallicity distribution function) and comparison with the metallicities in neutral absorption line gas will allow JWST to address the origin of the enriched intergalactic medium, the enrichment histories of different types of galaxies, and the degree to which merging or accretion of galaxies alters the metallicity of growing galaxies.

2.c. Focus 3: What Physical Processes Determine Galaxy Properties?

Some of main questions here are: • When and how are the global scaling relations for galaxies established? • Do luminous galaxies form through the hierarchical assembly of dark matter halos?

Global scaling relations: Despite the variety of galaxy properties observed today, galaxies obey a number of remarkably tight scaling relations between basic properties of luminosity, size, kinematics



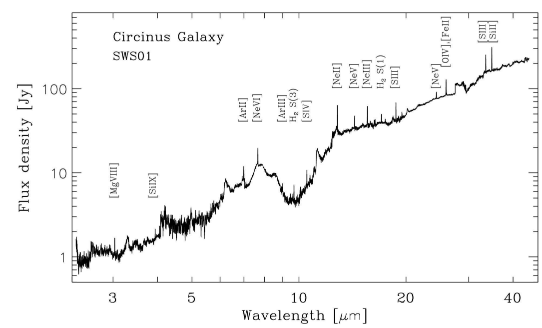


Fig. 2 (LEFT): Spectrum of a galaxy at z$\simeq$0.5, taken as part of the Canada-France Redshift Survey, shows O[II] to H α, the lines that make up the R_{23} index (from Lilly, Carollo & Stockton 2003). **Fig. 3 (RIGHT):** Mid-infrared ISO spectrum of the Circinus galaxy shows an abundance of emission lines useful for diagnosing the energy sources which power ULIRGs & AGN (from Moorwood et al. 1996).

and metal enrichment. These include the Tully-Fisher relation for disk galaxies (Tully & Fisher 1977) and the "fundamental plane", and projections thereof for spheroids (Faber & Jackson 1976; Kormendy 1977; Bender et al. 1992). More recently, a surprising relationship between the mass of the central black hole and the properties of the surrounding spheroid (e.g., the velocity dispersion) has been established (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). It is not known how or when these were established, and whether they represent an asymptotic (late-epoch) state, or whether they are obeyed at essentially all epochs (once allowance is made for the evolution of the stellar population). Simulations of galaxy formation have managed to reproduce the slopes, but not the normalizations of these dynamical relations. The compatibility of scaling relations based on color or metallicity with models in which most stars are formed outside of their eventual parent galaxies is not clear. Determination of the nature of these scaling laws at $1 \lesssim z \lesssim 7$, and of the scatter about them will likely reveal what physical process was responsible.

Hierarchical Assembly: In the standard CDM paradigm, the mass function of bound structures develops with time, as smaller objects are assembled hierarchically into larger ones, leading to an increase in the characteristic mass M^* in the Press-Schechter mass function (Press & Schechter 1974; Schechter 1976; Percival 2001). JWST images and spectra will study the evolution and organization of baryons in galaxies at high redshift, but will not reveal the underlying structures of non-luminous matter, which make up the gravitationally bound dark matter halos. It is the development of these halos which is the fundamental test of the CDM theory of galaxy formation.

2.d. Focus 4: What Roles do Starbursts & Black Holes Play during Galaxy Assembly?

Some of main questions here are: • What are the redshifts and power sources of the high-redshift ultra-luminous infrared galaxies (ULIRGs)? • What is the relation between the evolution of galaxies and the growth and development of super-massive black holes in their nuclei?

ULIRGs: The optical identification of high-redshift ULIRGs, found at sub-mm wavelengths, is extremely difficult with ground-based 8-10 m telescopes. The objects are very faint, and the detected images are at the confusion limits of the sub-mm telescopes. At present, none of the deepest field samples are securely identified at a level greater than 50%. Intensive efforts with ground-based telescopes will improve this before JWST's launch, but it is almost certain that many currently-known sub-mm sources will still be unidentified by the time JWST is launched. Spitzer observations have revealed the power of the mid-infrared in ULIRG and AGN identification (Ivison et al. 2004; Egami et al. 2004; Frayer et al. 2004). Analogs of known z$\simeq$2 ULIRGs — if they

Table 1: JWST Measurements for the Assembly of Galaxies Theme

Observation	Instrument	Depth (10σ/fwhm/$\Delta\lambda$)	Spectral Resolution	Target
1. Deep-wide survey (DWS)	NIRCam	3 nJy at 3.5μm	R$\sim$4	100 arcmin^2
2. Metallicity observations	NIRSpec	5×10^{-19} cgs	R$\simeq$1000	Galaxies in DWS
3. Scaling relations	MIRI	11 μJy at 9μm	R$\simeq$3000	LBG's at z$\simeq$3
	NIRCam	3 nJy at 3.5μm	R$\sim$4	DWS data
4. Obscured galaxies	MIRI	23 nJy at 5.6μm	R$\sim$4	ULIRGs
& AGN	NIRSpec	5×10^{-19} cgs	R$\simeq$1000	ULIRGs and AGN
	MIRI 24μm	1.4×10^{-16} cgs	R$\simeq$2000	ULIRGs and AGN

exist at z$\gtrsim$5 — will have remained unidentified from the ground until JWST, even though they may well already be present in today's sub-mm samples. The Atacama Large Millimeter Array (ALMA) will resolve the confusion in the sub-mm, but deep imaging with JWST at $\lambda\gtrsim2\mu$m is needed to identify these sub-mm sources.

AGN: A surprising discovery in galaxy studies of the last decade was that central black hole masses are tightly correlated with the bulge masses in present-day galaxies (e.g., Tremaine et al. 2002). These estimates have been extended using proxy indicators to redshifts z$\simeq$2 in QSOs, suggesting that this correlation may hold at high redshift (Shields et al. 2003; but see also Walter et al. 2004). Furthermore, the host galaxies of QSOs at redshifts z$\gtrsim$2 appear to be undergoing very high star-formation rates, while the peak in the quasar number density at z$\simeq$2 suggests that the formation of the central black hole keeps pace with the production of the bulk of the stellar population. However, the existence of some bright QSOs at z$\simeq$2–6 — with spectra that differ little from those with the lowest redshift — suggests that some super-massive black holes and their associated stellar populations formed very early in the history of the universe (Fan et al. 2001; Freudling et al. 2003). The close connection between central black holes and spheroid populations must be intimately connected with the process of galaxy assembly, and with the events that trigger and fuel active galactic nuclei (AGN) over cosmic time.

Supermassive black hole masses have also been measured by echo or reverberation mapping, maser kinematics, nuclear gas dynamics, nuclear star dynamics, and emission-line widths in AGN broad-line regions. They show a good level of agreement, and are probably correct to within a factor of two or three. Many of these methods will be applicable at high redshifts with JWST. Bulge stellar populations are characterized by the bulge luminosity profiles, velocity dispersion, and overall flux, with appropriate mass-to-light ratios according to the stellar populations. There are many questions that remain about the formation and evolution of super-massive black holes. We do not know if the seed black holes are primordial, if they form through the high-mass end of the population III mass function, and if they form over a wide range of redshifts. We do not know if their evolution traces the hierarchical growth of structure, or through merging within an initial stellar population, nor do we know the role of angular momentum, the role of accretion and feedback mechanisms in their growth, nor the redshift dependence of black hole mass growth.

3. Summary: What JWST will do on Galaxy Assembly over Cosmic Time

Table 1 summarizes the JWST measurements needed for the Assembly of Galaxies theme, including:

• **Deep-Wide Survey (DWS).** A deep-wide NIRCam survey will image the rest-frame UV–optical with 6–8 filters (typically $\gtrsim10\sigma$), yielding accurate photometric redshifts (Δz/(1+z)$\lesssim$0.05; e.g., Hogg et al. 1998) for essentially all galaxies brighter than the SMC at z$\lesssim$5 (AB$\lesssim$30.3 mag).

NIRSpec will measure the SFR of massive stars in a galaxy from its $H\alpha$ line to $5{\times}10^{-19}$ erg s^{-1} cm^{-2} (cgs), tracing star-formation rates of only $\sim$1 $M_{\odot}$ /yr at z$\simeq$5 (Kennicutt 1999).

• **Metallicity Determination.** Follow-up multi-object spectroscopy of hundreds to thousands of DWS galaxies will reveal the buildup of heavy elements as galaxies are assembled over cosmic time. NIRSpec multi-object spectra (at R$\simeq$1000 to separate $H\alpha$ and [NII]) will measure metallicities (to $\lesssim$0.2 dex) and [O/H] abundances from the R_{23} index (Pagel et al. 1979). R_{23} is based on strong emission lines such as [OII] λ3727, $H\beta$, [OIII] $\lambda\lambda$ 4959, 5007, $H\alpha$, [NII] λ6583, [SII] $\lambda\lambda$ 6717, 6731 (Fig. 2), and with these data JWST will trace all galaxies in the survey area with SFR $\lesssim$3 $M_{\odot}$ /yr yr at z$\lesssim$5.

• **Scaling relations.** JWST will provide deep NIRCam imaging for structural parameters plus high-resolution NIRSpec spectroscopy for kinematical data, yielding $H\alpha$ disk-rotation curves at high spatial resolution for z$\lesssim$5. MIRI spectroscopy of the CO bandhead at λ_{rest}=2.2 μm will yield velocity dispersions and the fundamental plane for R$\simeq$24.5 mag LBG's at z$\simeq$3, largely independent of metallicity and little affected by dust extinction. In addition, weak lensing analysis of the DWS data will reveal the relationship between the masses of galactic halos and the star light they contain (Zaritsky & White 1994; McKay et al. 2002; Wilson et al. 2001; Rhodes et al. 2004), but extending previous work from z$\simeq$0.1–1 to z$\simeq$2.5.

• **Obscured galaxies & AGN.** Imaging of ULIRGs will penetrate the obscuring dust to reveal the presence of merger-induced starbursts. Redshift identification of highly obscured systems can be done with $H\alpha$ out to z$\lesssim$6.5. R$\simeq$1000 spectroscopy will also reveal the kinematics of merging systems. MIRI spectroscopy of the [NeVI] 7.66 μm and 7.7μm PAH features (c.f., Fig. 3) will determine the energy sources that power these objects at z$\lesssim$2.5, since star-bursts have strong PAH features, while AGN have much weaker ones (Soifer et al. 2004; Armus et al. 2004).

Further details on the feasibility of these JWST observations to accomplish the four main Themes of "Galaxy Assembly over Cosmic Time" can be found in Gardner et al. (2006), Windhorst et al. (2006) and on the following URLs:
http://jwst.gsfc.nasa.gov/index.html and http://www.asu.edu/clas/hst/www/jwst/

Abbreviated References:

Abraham, R., ea. 1996, MNRAS, 279, L47
Abraham, R., ea. 1999, MNRAS, 303, 641
Abraham, R., ea. 2004, AJ, 127, 2455
Armus, L., et al. 2004, ApJS, 154, 178
Barmby, P., et al. 2004, ApJS, 154, 97
Bender, R., et al. 1992, ApJ, 399, 462
Bouwens, R., et al. 2005a, ApJ, 624, L5
Bouwens, R., et al. 2003, ApJ, 593, 640
Brinchmann, J., et al. 1998, ApJ, 499, 112
Chary, R., et al. 2004, ApJS, 154, 80
Cole, S., et al. 1994, MNRAS, 271, 781
Cowie, L., et al. 1995, Nature, 377, 603
Dickinson, M. 2000, Phil. Tr. R. Soc., 358, 2001
Driver, S., et al. 1995, ApJ, 449, L23
Driver, S., et al. 1998, ApJL, 496, L93
Egami, E., et al. 2004, ApJS, 154, 130
Faber, S. & Jackson 1976, ApJ, 204, 668
Fan, X., et al. 2001, AJ, 122, 2833
Ferrarese, & Merritt 2000, ApJ, 539, L9
Franx, M., et al. 2003, ApJ, 587, L79
Frayer, D., et al. 2004, ApJS, 154, 137
Freudling, W., et al. 2003, ApJ, 587, L67
Gardner ea. 2006, Sp.Sc.Rev. 123, 485
Gardner, J., et al. 2009, Astro 2010
Gebhardt, K., et al. 2000, ApJ, 539, L13
Giavalisco, M., et al. 1996, ApJ, 470, 189
Hamann, F., & Ferland, G. 1999, ARA&A, 37, 487
Hogg, D., et al. 1998, AJ, 115, 1418
Hu, E., et al. 2002, ApJ, 568, L75
Hu, E., et al. 2004, AJ, 127, 563
Ivison, R., et al. 2004, ApJS, 154, 124
Kennicutt, R. C. 1999, ApJ, 525, 1165
Kormendy, J., 1977, ApJ, 218, 333
Labbé, I., et al. 2005, ApJ, 624, L81
Lilly, S., et al. 1995, ApJ, 455, 108
Lilly, S., et al. 2003, ApJ, 597, 730
McCarthy, P., et al. 2004, ApJ, 614, L9
McKay, T., et al. 2002, ApJ, 571, L85
Meixner, M. et al. 2009, Astro 2010
Moorwood, A., ea. 1996, A&A, 315, L109
Pagel, B., et al. 1979, MNRAS, 189, 95
Percival, W. J. 2001, MNRAS, 327, 1313
Press & Schechter 1974, ApJ, 187, 425
Rhoads, J., et al. 2003, AJ, 125, 1006
Rhodes, J., et al. 2004, ApJ, 605, 29
Schade, D., et al. 1995, ApJ, 451, L1
Schechter, P. 1976, ApJ, 203, 297
Shields, G., et al. 2003, ApJ, 583, 124
Soifer, B., et al. 2004, ApJS, 154, 151
Sonneborn, G. et al. 2009, Astro 2010
Steidel, C. et al. 1999, ApJ, 519, 1
Stiavelli, M. et al. 2009, Astro 2010
Tremaine, S., et al. 2002, ApJ, 574, 740
Vogt, N., et al. 1996, ApJ, 465, L15
Vogt, N., et al. 1997, ApJ, 479, L121
Walter, F., et al. 2004, ApJ, 615, L17
White, S., & Frenk, C. 1991, ApJ, 379, 52
Wilson, G., et al. 2001, ApJ, 555, 572
Windhorst, R., et al. 2006, NewAR, 50, 113
Yan & Windhorst 2004a, ApJ, 600, L1
Yan & Windhorst 2004b, ApJ, 612, L93
Zaritsky, D., & White 1994, ApJ, 435, 599
Zepf, S., 1997, Nature, 390, 377