Reionization to Exoplanets: Spitzer's Growing Legacy
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Young Galaxies as Seen by Spitzer: Cold and Warm

Giovanni G. Fazio

Harvard Smithsonian Center for Astrophysics, MS/65, 60 Garden St., Cambridge, MA 02138, USA

Abstract.
One of the most important observations made by the Spitzer Space Telescope has been the detection of luminous galaxies back to the era of reionization (z $\sim$ 8), when the universe was less than 700 million years old. The key advance made by Spitzer imaging is the ability, for the first time, to sample the redshifted rest-frame visible light of these galaxies. When combined with broadband multi-wavelength data, Spitzer observations can be fit to stellar population synthesis models to determine the spectral energy distribution of these galaxies and to constrain their stellar masses and ages and their star formation histories. As a result, there is evidence that most of the stellar mass of these galaxies formed at even higher redshifts (z > 10 - 12), and that a significant number of galaxies should exist in this region. Searches for galaxies at z $\sim$ 9-10 continue. Spitzer observations of massive lensing clusters have also played a pivotal role in this study. The first IRAC detection of a z > 6 galaxy came from such observations. Since most of these results were obtained with Spitzer/IRAC 3.6/4.5 μm bands, the Spitzer Warm Mission, when combined with future HST/WFC3 observations, will provide a unique opportunity to obtain the first complete census of the assembly of stellar mass as a function of cosmic time back to the era of reionization, yielding unique information on galaxy formation in the early Universe.

1 IRAC Observations of the Early Universe

One of the original scientific objectives of IRAC (Fazio et al. 2004) was to understand the formation and evolution of normal galaxies to redshifts z > 3 by means of deep surveys in the four IRAC bands. At the time (early-1990s) this limit was selected because it was apparently beyond the peak in the known space density of luminous quasars. Specifically, the IRAC sensitivity requirement was set by the need to determine the spectral energy distribution (SED) of a L* galaxy at z = 3. The four IRAC filters were originally designed to determine the photometric redshift of galaxies, based on the 1.6 μm peak (due to the H- opacity minimum in the atmospheres of late type stars) and the 2.3 μm CO absorption feature (Wright et al. 1993; Simpson & Eisenhardt 1999). As shown in Figure 1, the 1.6 and 2.3 μm features appear early in galaxy spectra and are persistent with galaxy age. It is also important to note from Figure 1 that, for the first time at high redshift, Spitzer/IRAC offered access to the rest-frame visible light of galaxies, longward of the Balmer break.

In summary, Spitzer/IRAC provides a unique perspective for observations of the early universe: (1) the IRAC filters (3 to 9 μm) probe, for the first time,

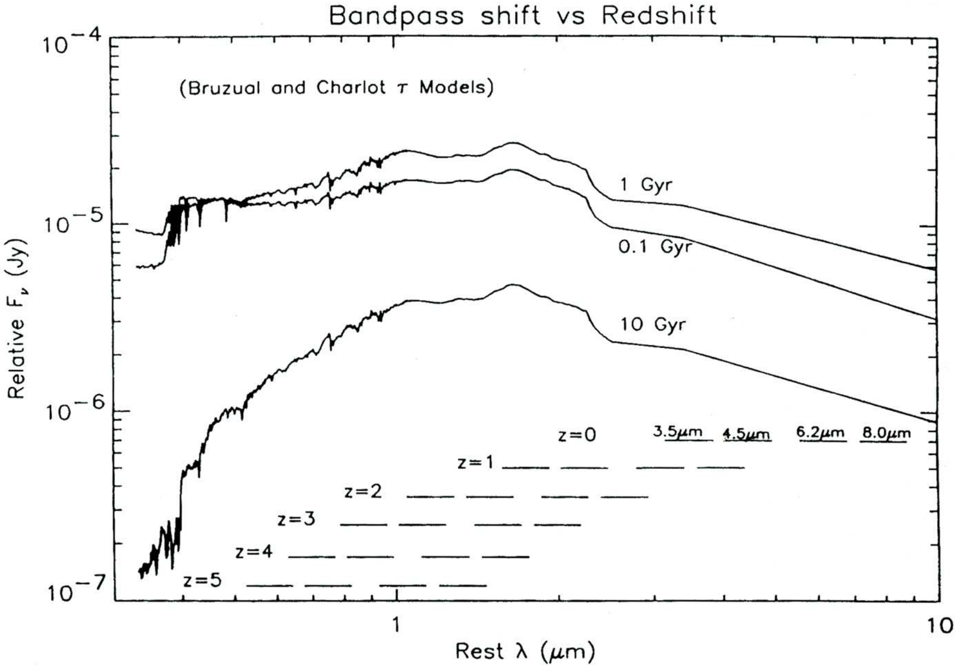

Figure 1. Predicted spectra of galaxies aged 0.1, 1, and 10 Gyr old (Bruzual & Charlot 1993). Note the early appearance and persistence of the features at 1.6 and 2.3 μm.

the rest-frame optical and near-IR light at high redshifts; (2) these observations, when compared to rest-frame ultraviolet observations, are less affected by dust extinction; (3) IRAC observations provide the first view of light from longer-lived stars that dominate the stellar mass of high redshift galaxies; (4) from these observations the unique properties of a galaxy's stellar mass and age can be determined; and (4) they enable a new perspective on the study of early galaxy formation and evolution. In actual practice, using IRAC color-color diagrams based on the four IRAC bands only (e.g. [3.6]-[4.5] vs. [5.8]-[8.0]), to identify high z galaxies is practical only to z $\sim$ 2-3. Beyond this redshift range the sensitivity of the 4.5 and 8.0 μm bands are insufficient to detect galaxies. Therefore, other techniques, based on optical and near-IR wavelengths have to be used select high redshift galaxies.

2 Identifying High Redshift Galaxies

One method used to identify high redshift galaxies in a multi-wavelength survey is the Lyman Break Galaxy (LBG) technique, which was first developed by Steidel et al. (1996, 1999). This method uses the Lyman break at 912 Å and the dimming between 912 and 1216 Å due to the Lyman-alpha forest in a galaxy spectrum to identify its redshift. Since the observed wavelength is (1+z) times the rest-frame wavelength, absence of a signal in the wavelength band shortward of the Lyman break can be used to measure z. Thus a B-band dropout indicates z=4; V-band z=5; i-band z=6; z-band z=7; Y-band z=8 and J-band z=10, etc. The second technique for identifying high redshift galaxies is use the Lyman-alpha Emitter (LAE) technique. This method uses a narrow band filter (100-200 Å wide) to detect the Lyman-alpha emission line (1216 Å) from atomic hydrogen in a galaxy spectrum. The filter is positioned in a wavelength band between the night sky emission lines to reduce the background emission. A sky survey is then carried out in both the narrow-band filter and a wide-band filter that includes the narrow-band wavelength. Comparison of the images taken with the two filters permits identification of the Lyman-alpha emission galaxy. For example, a narrow-band filter at 9730 Å can identify a Lyman-alpha emission galaxy at z $\sim$ 7 (Ota et al. 2008).

3 IRAC Observations of Galaxies at z = 5 to 7 (1.2 to 0.78 Gyr after Big Bang)

Using the Lyman Break Technique, Eyles et al. (2005) presented evidence for one of the first HST and Spitzer/IRAC detections of galaxies at z $\sim$ 6. Using the HST Great Observatories Origins Deep Survey (GOODS) in B-, V-, I-, and z-bands and the IRAC bands and applying the I-band dropout technique, they identified four z $\sim$ 6 galaxies, two of which had IRAC detections in the 3.6 and 4.5 μm bands (Figure 2). The redshift was later spectroscopically confirmed using the Keck telescope. From the model fit it was determined that the galaxy SBM03 #1 was massive (2.3 x 10^{10} $M_\odot$). The Spitzer/IRAC photometry revealed a significant Balmer discontinuity which indicated that the galaxy contained a mature stellar population with ages $\sim$ 400 Myr old, which implied formation redshift of z > 7. Without the IRAC mid-infrared photometry to very faint magnitudes, the stellar ages and masses of z > 5 galaxies are poorly constrained. These observations indicated that galaxies with stellar masses > 20% of those of a present-day L* galaxy had already assembled within the first Gyr after the Big Bang. The average star formation rate deduced was 5-30 $M_\odot$ per year. Similar results were reported by Yan et al. (2005) and Dow-Hygelund et al. (2005).

The evolution of LBGs between z = 4-6 by Stark et al. (2009), using HST/ACS and Spitzer/IRAC/MIPS observations in GOODS, showed that no strong evolution of stellar masses and stellar ages of galaxies of fixed UV luminosity existed between z = 6-4, and that this was consistent with the drop in UV luminosity function between z = 4-6. They also presented evidence that the stellar mass function of UV luminous galaxies grows significantly from z = 6-4.

4 Observations of Galaxies at z > 7 (< 800 Myr after the Big Bang)

Labbe et al. (2006) extended the galaxy mass estimates to z = 7-8 using very deep (25-27 mag AB) IRAC observations of six z-band dropout candidates found in GOODS observations of the Hubble Ultra-Deep Field (HUDF). Two of the candidates were clearly detected by IRAC. This redshift region is of particular importance since it is in the reionization era of the Big Bang model. Again, the IRAC observations allow, for the first time, the ability to constrain the rest-frame optical colors, stellar masses, and ages of the highest redshift galaxies. Labbe et al. (2006), fitting stellar population models to the spectral energy distributions

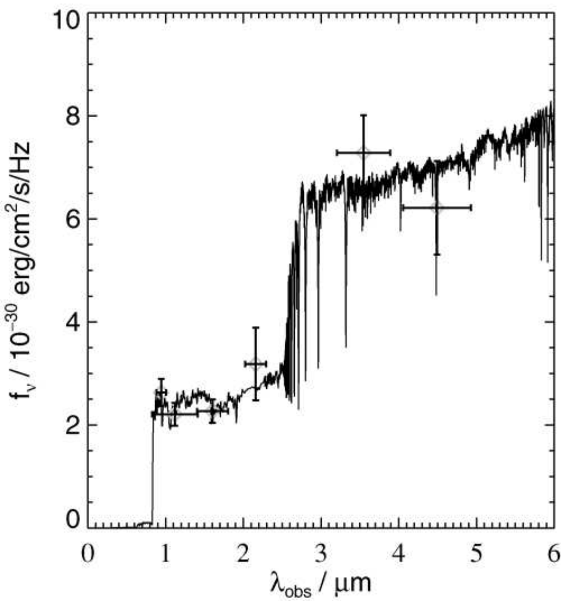

Figure 2. Observed spectrum of the z = 5.83 galaxy SBM03#1 fit with a Bruzual & Charlot (2003) model (Eyles et al. 2005).

determined photometric redshifts in the range 6.7 to 7.4, stellar masses (1-10) x 10^9 $M_\odot$, stellar ages 50-200 Myr, star formation rates up to $\sim$ 25 $M_\odot$ per year, and low reddening. The z = 7 galaxies appear to be much less massive and evolved than the galaxies at z = 2-3, but similar to the masses measured at z = 5-6. Again the indication is that these z = 7 galaxies formed at z > 8, during the era of cosmic reionization. However, the star formation rate density derived for these objects from their stellar masses and ages is more than 3 times too small to reionize the universe. These results imply that low-mass galaxies beyond the current detection limit were primarily responsible for reionization. Gonzalez et al. (2010) reported similar results from a more robust sample of 11 z = 7 galaxies (z-band dropouts) detected by IRAC. They also concluded that the specific star formation rate at a given galaxy mass value is a constant as a function of redshift from z = 7 to z = 2 but drops suddenly at z = 2, and that the stellar mass density decreases as a function of redshift (Figure 3).

IRAC observations of sub-L* galaxies in the region between z $\sim$ 7 and 8 by Labbe et al. (2010) yielded important insights into the earliest phases of galaxy evolution. These results yielded relatively high stellar ages ($\sim$ 300 Myr) for these galaxies and demonstrated that the specific star formation rate does not depend on stellar mass. They also observed a significant contribution of low luminosity galaxies (0.06 L* at z = 3) to the stellar mass density at z $\sim$ 7, and concluded that the stellar mass seen in these galaxies could provide a substantial contribution to the reionization of the universe. The evolution of galaxies in the redshift range z = 7-8 based on recent HST/WFC3 and Spitzer/IRAC observations (see Labbe et al. 2009) in the Hubble Ultra Deep Field (HUDF09) yielded 21 z $\sim$ 7 (z-band dropouts) and 3 z $\sim$ 8 (Y-band dropouts). Galaxies with z $\sim$ 7 have high ages (> 300 Myr) and their derived stellar masses correlate well with the star formation rate (Figure 4).

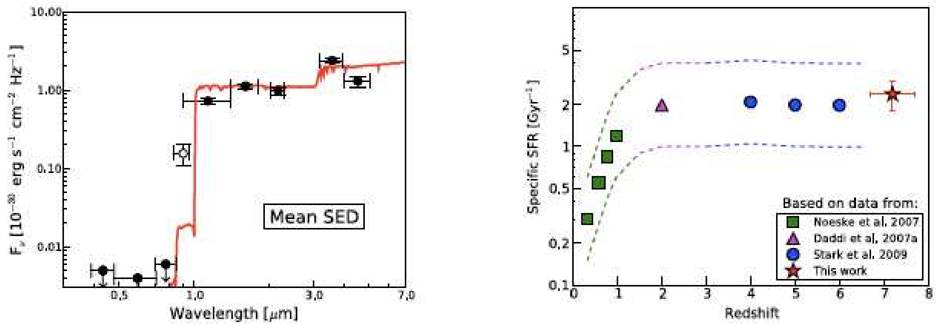

Figure 3. Left: Average SED derived from the 11 z = 7 sources detected by Gonzalez et al. (2010). Right: The specific star formation rate derived from the z = 7 galaxies combined with previous results at a constant galaxy mass of 5 x 10^9 $M_\odot$.

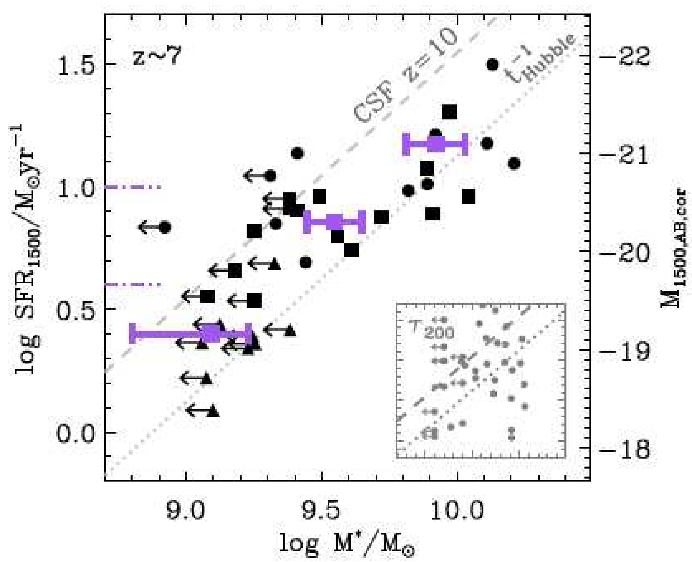

Figure 4. UV-derived, dust-corrected star formation rate versus stellar mass for z ~ 7 galaxies. Data from NICMOS (circles), WFC3/IR ERS (squares), and WFC3/IR HUDF sample (triangles). The large bars show the average stellar mass in bins of star formation rate centered on log SFR = 0.4, 0.8, and 1.2 (Labbe et al. 2009).

The first robust Spitzer/IRAC detection of a Y-band dropout galaxy at z ~ 8 (650 Myr after the Big Bang) was also reported by Labbe et al. (2009). The magnitude of the Balmer break was indicative of an evolved stellar population. This galaxy had a similar age (~ 300 Myr) to the z ~ 7 galaxies, suggesting modest to no evolution between z = 7 and z = 8. These results also implied that initial star formation occurred at z ~ 12. Labbe et al. (2009) also showed that the stellar mass density decreased as $(1+z)^{-6}$ between z = 4-8 (Figure 5). The search for z = 10 galaxies (500 Myr after the Big Bang) by Bouwens et al. (2004), using observations with the HST/WFC3/IR in the HUDF, found three

J-band dropouts, visible in H-band only. Stacking of the IRAC data yielded no detection.

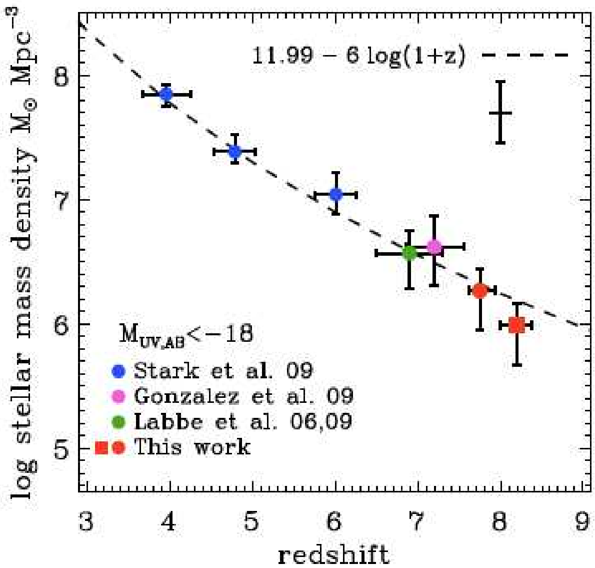

Figure 5. Evolution of the integrated stellar mass density from z = 4-8 (Labbe et al. 2009). The data at z = 4-6 is from Stark et al. (2009); the data at z = 7 is from Gonzalez et al. (2010) and Labbe et al. (2006, 2009); and the data at z > 7 from Labbe et al. (2010). The floating error bar indicates the expected cosmic variance for the z ∼ 8 samples.

5 The Search for Lensed Galaxies at z ∼ 7

The first high-z galaxy detected by IRAC was the result of a search for lensed high redshift galaxies in massive galaxy clusters (Egami et al. 2004). A galaxy at z ∼ 7 was detected lensed by the cluster Abell 2218. The gravitationally lensed objects, with a magnification of 25, were discovered by Kneib et al. (2004) in HST images. By fitting a Bruzual-Charlot model to the HST and Spitzer/IRAC data the photometric redshift measured was z = 6.6-6.8. A significant Balmer break gave a stellar age of 100-400 Myr, which implied the stars formed at 9 < z < 12. The star formation rate was $\sim 2.5\ M_\odot$ per year and the stellar mass of the galaxy was $\sim 10^9\ M_\odot$. Bradley et al. (2008), using HST, found a lensed galaxy at z ∼ 7.6 in the massive galaxy cluster Abell 1689, which was also detected by IRAC. They observed that the magnification was ∼ 9.3 and that star formation was occurring in compact knots of ∼ 300 pc.

6 A Search for the First Stars (∼ 200 Myr after the Big Bang)

Kashlinsky et al. (2005) reported measurements, using IRAC, of diffuse flux fluctuations in the cosmic infrared background radiation. These fluctuations were detected in deep IRAC surveys after removing foreground stars and galaxies and noting that the measured anisotropies exceeded the instrument noise and local foreground radiation fluctuations. The amplitude of the fluctuations was $\sim$ 0.1-0.3 nW m^{-2} sr^{-1} at 3.6 to 8 μm wavelength on scales of $\sim$ 1 arcmin. Kashlinsky (2005) and Kashlinsky et al. (2005) interpreted these results as evidence for a first light component (Population III stars) at z > 8. However, the redshift of these fluctuations was unknown. Cooray et al. (2007) and Chary et al. (2008), using HST/ACS observations, concluded the effect could be due to undetected dwarf galaxies at z $\sim$ 1-3. Thompson et al. (2007) using HST/NICMOS near-IR data reported only upper limits to any fluctuations and concluded their results were inconsistent with a Population III star interpretation. Future, more extensive observations are planned with the Spitzer Warm Mission to try to resolve these conflicts.

7 Future Observations to Search for High Redshift Galaxies

The searches thus far for high redshift galaxies have been limited to rather small areas (< 0.1 square degree) or with a small number of massive galaxy clusters. Two major Spitzer Warm Mission Exploration Programs and a HST Cosmology Survey Multi-Cycle Treasury Program will soon provide much larger survey areas and more sensitive observations to search for high z galaxies as well as a larger number of massive lensed clusters. However, the ultimate study of the early universe will be carried out by the James Webb Space Telescope (JWST), which will launched in 2014.

The Spitzer Extended Deep Survey (SEDS; G. Fazio, PI) will provide a unique opportunity to obtain the first complete census of the assembly of stellar mass and black holes as a function of cosmic time back to the era of reionization, yielding unique information on galaxy formation in the early Universe. The survey will also measure galaxy clustering over a wide redshift range, which will provide the critical link between galaxies and their dark matter halos and critical tests of models of early star formation. SEDS will achieve these goals by tracing the stellar mass growth in mass selected samples of galaxies via their broadband spectral energy distributions. The baseline proposal is an unbiased survey with 12 hours/pointing at 3.6 and 4.5 μm over five well-studied fields of 0.90 square degree total. The survey expects to find (a) >10,000 galaxies at z = 4-6 (including $\sim$1000 galaxies at z = 6), reaching galaxies down to $\sim$5 x 10^9 $M_\odot$ at z = 6, necessary to robustly measure M* at that redshift, i.e., the galaxies that dominate the global stellar mass density, and (b) >100 massive galaxies at z = 7, which will firmly anchor the high mass end of the early galaxy populations and provide targets bright enough for future spectroscopic follow up with 20-30 meter telescopes, JWST, and ALMA. The proposed five field deep survey will enable several secondary science objectives. These include: (1) galaxy evolution in the redshift range z $\sim$ 1-4, (2) AGN variability, and (3) measurement of the cosmic infrared background spatial fluctuations.

Massive clusters of galaxies are now recognized as very effective "cosmic telescopes." Because of the gravitational lensing effect, they can amplify significantly the background sources (by factors of a few tens) thereby bringing into view faint sources that would otherwise be unobservable. Note that in the background-limited case, which is applicable to IRAC observations, a factor of 20-30 gravitational amplification translates into increasing the integration time by a factor of 400-900. Because of this tremendous gain in sensitivity, IRAC imaging of lensing clusters will permit JWST depth (~10 nJy) to be achieved with Spitzer. Despite this great possibility, however, the full potential of the lensing cluster technique has not yet been realized due to the small number of clusters that have well constrained accurate mass models. During the Spitzer Warm Mission Exploration Program, E. Egami (PI) will conduct an IRAC imaging survey of 47 massive lensing clusters (5 hours/band, 2 bands) for which accurate mass models have been developed through many years of intensive imaging/spectroscopic campaigns with HST, Keck, and VLT telescopes. This is the first time when such a large, statistical sample of such well-characterized clusters will be systematically employed to probe the high redshift universe. This IRAC survey is a key component of a more comprehensive program, which includes HST/WFC3 and Herschel observations in 2010. Scientifically, IRAC data will be used to (1) characterize z > 6 galaxies (expecting ~50 z$\sim 7-8$ galaxy detections), (2) support future Herschel and ALMA surveys, and (3) search for z>6 supernovae.

The HST Cosmology Multi-Cycle Treasury Proposal survey (S. Faber, PI; H. Ferguson, Co-PI) will document the first third of galactic evolution from z = 8 to 1.5 and test for evolution in the properties of Type Ia supernovae to z~2 by imaging more than 250,000 galaxies with HST WFC3/IR and ACS. Five premier multi-wavelength regions were selected from within the Spitzer SEDS survey, providing complementary IRAC data down to 26.5 AB mag, and a unique resource for stellar masses at high redshifts. The use of five widely separated fields mitigates cosmic variance and yields statistically robust samples of galaxies down to 10^9 $M_\odot$ out to z~8. The program incorporates a two-tiered strategy using a "Wide" component (2 orbits deep over ~0.2 sq. degrees) and a "Deep" component (12 orbits deep over ~0.04 sq. degrees). Combining these with ultra-deep imaging from the Cycle 17 HUDF09 program yields a three-tiered strategy for efficient sampling of both rare/bright and faint/common objects.

One of the key science goals of the JWST is to study the first light sources and the era of reionization of the universe. It will identify the first luminous sources to form and will determine the ionization history of the early universe. JWST is a large (6.6-meter) cold (< 50K), infrared-optimized space telescope, which will orbit around the second Earth-Sun Lagrange point. The observatory will have four instruments: a near-infrared camera (NIRCam), a near-infrared multi-object spectrograph (NIRSpec), and a tunable filter imager (TFI) which will cover the wavelength range from 0.6 to 5.0 μm, and a mid-infrared camera/spectrometer (MIRI) which will cover the wavelength range from 5.0 to 29 μm.

8 Summary

Detecting the most distance galaxies known in the Universe, back to the era of reionization (z $\sim$ 8), has been one of most remarkable achievements of Spitzer Space Telescope (85-cm mirror). Dramatic new results on this topic have been achieved over the last year.

When combined with deep, broadband multi-wavelength data, Spitzer observations can be fit to stellar population synthesis models to determine, for the first time, the spectral energy distribution of these galaxies and to constrain their stellar masses and ages and their star formation histories.

These results have enabled a new perspective on studies of early galaxy formation: (1) massive galaxies ($\sim 10^{10}\ M_{\odot}$) with stellar ages (~200-300 Myr) existed in early Universe (z $\sim$ 6-8); (2) the stars in these galaxies formed several hundred years earlier (z $\sim$ 8-12); (3) comprehensive measures of the stellar mass density exist over $4 < z < 8$; (4) stellar mass correlates well with SFR; (5) evidence exists for constant SFR from z $\sim$ 10-12; (6) there exists a substantial contribution of low luminosity galaxies at z=7 that could provide a significant fraction of the energy to ionize the Universe.

The Spitzer Warm Mission/HST will provide a unique opportunity to obtain the first complete census of the assembly of stellar mass as a function of cosmic time back into the era of reionization, yielding unique information on galaxy formation in the early Universe.

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