Modelling the Properties of High Mass Galaxies at High Redshift

by

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Abstract

Modelling the Properties of High Mass Galaxies at High Redshift

by *Ryan Brown*

submitted on May 24, 2015:

A set of galaxies observed at high redshift were modelled to investigate the star formation history and other properties of these galaxies. By the gzK Selection Technique, twelve galaxies from the Canada-France-Hawaii Telescope Legacy survey were selected from the region of gzK colour-colour space that categorizes quiescent galaxies. Using observed magnitudes in the u, g, r, i, z, J, H, K filters, the galaxies were fit to spectral models using the software SEDfit. From comparison of χ^2 values between best fitting quiescent/star forming models, the passive quiescent galaxy model was found to best represent the set of galaxies. This best fit quiescent model has galaxies properties of approximately: galaxy masses on the scale of 5×10^{11} solar masses, galaxy ages of 0.89 Gyr, redshifts in the range of approximately 2.1 to 2.4, and present no dust or star formation. Model fitting without the J and H filter magnitudes show that galaxy age is not affected by the presence/absence of these filters, but mass and redshift are dependent on J and H filters. Without J and H filters, the mass and redshift are overestimated by a factor of 60% and 20% repsectively.

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Chapter 1

Introduction

1.1 Background

1.1.1 Galaxy Evolution

The current distribution, morphologies, and properties of galaxies is the result of billions of years of various cosmic processes and initial conditions of the Universe. Galaxies evolve as they form stars from interstellar dust and gas over billions of years, and can be observed in one of two states, active and star forming or passive and quiescent (Kauffmann et al. (2003)), which is observed at redshifts from $z = 0$ to out as far as $z \sim 2$ (Muzzin et al. (2013)). Active star formation will occur in the presence of dust and gas, which collapses into protostars; otherwise without dust or gas the formation of stars will cease and the galaxy becomes quiescent.

Objects in the night sky, such as the galaxies in question, are not observed as they are now (at time of observation) but as they once were. This is because the method used to observe objects in space is by receiving the light they emit, and since the speed of light is a finite value, there is a lag in the time the light is emitted and the time the light is detected by observation. This lag, known as lookback time, allows observations to be made of the past conditions of the cosmos. Since observations can be made to multiple look back times, as objects at different distances have different lookback times by merit of the speed of light, a timeline of galaxies can be observed in modern time. Given a large enough sample size, a statistical distribution of galaxy properties for different periods of the Universe's history can be made. From such a statistical map of galaxy evolutionary history, a generalized model of how galaxies evolve can be constructed. Thus the collection and study of galaxies at various lookback times is necessary for the assembling a model of galaxy evolution. From the properties of the galaxy populations, the various models of galaxy formation and evolution can be constrained by the observations. Values of mass, age, redshift, extinction, and SFR can help place constraints on the space of possible models.

Observations of galaxies at high redshift reveal the existence of potentially quiescent, high mass (with masses of approximately 10^{11} solar masses) galaxies present in the early Universe of redshift $z \sim 2$. That a large number of massive, "dead" galaxies this early in the Universe rises questions about their evolution; how did these young galaxies form so many stars over such a short cosmological time, and how did they become quiescent during a period of the Universe where dust and gas to make stars would be more plentiful? From the currently accepted cosmological model of the Universe, redshift z $\sim$ 2 corresponds to when the Universe was approximately 3.3 Gyr old (Wright (2006)), which also happens to be when star formation in the universe peaked (Madau and Dickinson (2014)), which would require that these massive quiescent galaxies formed very shortly in the early universe before quenching during the most active period of star formation in cosmological history. Assuming these galaxies formed on the star-forming main sequence for galaxies, these galaxies must have assembled their $\sim 10^{11} M_\odot$ with star formation rates (SFR) of $100 - 500\ M_\odot/yr$ near the end of their evolution.

As these objects are of high mass, they are most likely to be the central galaxy/galaxies of their respective dark matter halos, as the centre of mass of a halo is where any matter will gravitate about. Thus the identification of these high mass galaxies corresponds with locating the dark matter distribution of that cosmological era. Any inhomogeneous distribution in mass in the form of dark matter will slowly collapse under gravity into denser halos, in which dust and gas that form galaxies will collapse into, facilitating galaxy formation.

Understanding of how galaxies evolve is contingent on understanding these peculiar quiescent, massive objects.

1.1.2 BzK Secection

The BzK Selection Technique, which differentiates passive quiescent galaxies from active star forming galaxies, uses b, z, and K filter magnitudes to determine a BzK value (Daddi et al. (2004)). The value for BzK is determined by the equation:

$$BzK = (z - K) - (b - z), \tag{1.1}$$

where $(z - K)$ and $(b - z)$ are the z-K and b-z colours. From other observations involving [O II] emission and C IV absorption (Daddi et al. (2004)), objects with $BzK \geq -0.2$ correspond to star forming galaxies at redshifts greater than $z = 1.4$, otherwise the galaxies are passive (quiescent) if they meet the criteria of:

$$BzK < -0.2 \ and \ (z - K) > 2.5. \tag{1.2}$$

With these two criteria, galaxies can be selected based on whether or not they are quiescent or star forming for redshifts between $1.4 \leq z \leq 2.5$.

1.1.3 Modifying BzK to gzK

For cases where BzK Selection cannot be used directly, if one or more of the b, z, or K are not present, a modified version selection method is required. Data sets such as the CFHT LS, do not have a b filter, only the adjacent filters of u and g. Naively, substituting either the u or g filter of the b filter would be an ideal solution, as these filters have wavelength sensitivity adjacent to the b filter wavelengths. Comparing the colour-colour diagrams between BzK and gzK (see Figure 1.1), the features of the colour-colour diagrams are similar for both selection methods (Arcia-Osejo and Sawicki (2013)). Thus gzK Selection can be used as a substitution to BzK selection.

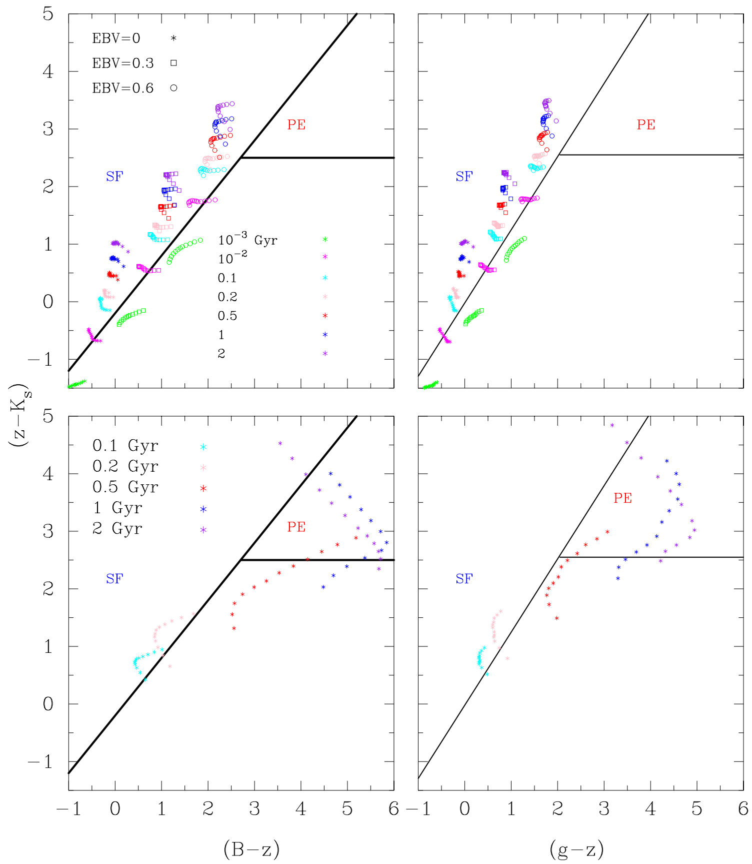

Figure 1.1: Two pairs of colour-colour diagrams, one on the left for BzK Selection and the one of the right for gzK Selection. Each set of data points is model galaxy on the colour-colour diagram, over a range of redshifts between $1.4 \leq z \leq 2.5$. The colour of the data points correspond to the age of the model galaxies, the shape of the data points correspond to variations in model extinction. (Arcia-Osejo and Sawicki (2013))

For gzK Selection, the criteria for selecting passive, quiescent galaxies as defined by Equation 1.3 (Arcia-Osejo and Sawicki (2013)):

$$gzK = (z - K) - 1.27(g - z) < -0.022 \ and \ (z - K) > 2.55 \tag{1.3}$$

1.2 Objects

The twelve high mass, high redshift galaxies subject to this model fitting were selected by the gzK Selection Technique from the Canada-France-Hawaii Telescope Legacy Survey (CFHT LS-Deep) as part of a observation project with the Gemini telescopes to better confirm values of redshift, age, and quiescence. This Gemini observation will also attempt to detect AGn in the selected galaxies, collect better spectroscopic data from these galaxies, and constrain the stellar mass function(SMF) of these high redshift objects for galaxies of high mass (such as these selected objects). These galaxies were selected by the gzK criteria to be passive quiescent galaxies, which modelling of their star formation history will either confirm or discredit this selection. The regions of sky these objects were taken from the CFHT LS-Deep correlate with previous surveys such as COSMOS and were spaced out across the sky as four fields to account for variance in the fields(Arcia-Osejo and Sawicki (2013)). Th detection of objects and photometry of these fields was performed with the software SExtractor, to both detect objects and measure fluxes in the k band filter images. While the objects were detected with unsmoothed images, the photometry was done using smoothed images. The field images were smoothed to match the worst seeing in the field, as a means of accounting for variance in the seeing in the field. The fluxes were then measured with equal sized, 10 pixel diameter apertures with SExtractor, centred on the positions of the unsmoothed image detections (Arcia-Osejo and Sawicki (2013)).

1.3 Objective

To fully understand these objects and their evolutionary history, three important questions must be answered: 1) Are these galaxies quiescent or star forming at the time they are being observed? 2) What are the masses, ages, redshifts, star formation rates, and dust extinctions of these galaxies? 3) How important is information from various infrared filters (such as J ad H) in determining the properties of these galaxies?

1.3.1 Quiescent or Star Forming?

Since these galaxies were selected with gzK_s Selection to be quiescent, the data should be modelled to check that these galaxies are in fact quiescent. gzK_s Selection was used to select these galaxies as potential quiescent galaxies, but it is possible some objects may be misidentified as quiescent galaxies if for some reason they still meet the criteria of gzK_s Selection Technique. If these objects are not quiescent, despite matching the criteria of the gzK_s selection, then information from a larger set of filters could help identify these objects are not passive quiescent. If modelling favours star forming galaxy models over passive quiescent galaxy models, then these galaxies are not objects gzK_s Selection can properly identify.

1.3.2 Galaxy Properties

The masses, ages, redshifts, SFRs, and extinctions of these galaxies are also important in the understanding of galactic evolution, as these values place constraints on potential models of galaxy evolution.

1.3.3 Importance of Other Filters

Since gzK_s Selection uses $g - z$ and $z - K$ colours in the selection process, the only infrared filters needed for this selection technique are z (near-infrared) and K (far-infrared). Just three filters, which cover a wide range of wavelengths, provide little information about the galaxy spectrum. Other features such as emission line, absorption lines, and magnitude breaks are unlikely to cluster about these three filter wavelengths, so other filters are needed to probe information on the spectrum features (and thus the galaxy properties that cause these features) in detail.

Intermediate infrared filters such as J and H are not needed in the gzK_s Selection, but information from these intermediate filter wavelengths might be useful, if not necessary, in understanding the properties of these galaxies. Redshift is determined by identifying spectral features at shifted wavelengths, and if the features used are shifted to wavelengths intermediate to z and K, calculations of redshift may not be accurate. If J and H filter data is important in the modelling, then other properties such as mass and age may also be affected. For surveys such as CFHT LS-Wide, which do not have a J and H filter, whether or not these filters are necessary could be be important to any science done from this data.

Chapter 2

Procedure

2.1 Methods

2.1.1 SEDfit

To model the galaxies, the observed magnitudes of the u, g, r, i, z, J, H, K filters are compared to theoretical spectra. These spectra are generated by a program called GALAXEV (Bruzual and Charlot (2003)), which generates the spectra based on star formation history (as well as other parameters such as metallicity, which are not changed or varied in this modelling) for a single stellar mass population (Golob (2013)). The software SEDfit then takes these spectra and generates a model space of possible redshifts and dust extinctions for the imputed cosmological model. The filter data then is compared to the model space by brute force, where every model in the model space is systematically compared to the data one by one, scaling the mass to fit the data (Sawicki (2012)).

When generating the models, SEDfit allows for variation in the values of extinction and redshift; a range can be chosen as well as the step size the software will use to cover this range. For these objects, extinction was set so that SEDfit generates models of $E(B-V)$ between 0.00 and 1.00 in steps of 0.02 and redshift was set to generate models with z between 0.0 and 5.0 in steps of 0.02. Thus 12500 different models were generated for each permutation of extinction and redshift for each of the star formation histories.

Other parameters that can be adjusted by SEDfit include the type of dust model, the cosmological model applied to the model universe, and the cosmic opacity. For this modelling, these parameters were left to their standard values; the Calzetti extinction law (Calzetti (2001)), the flat matter-dark energy universe cosmological model ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, Hubble Parameter $H_0 = 70$ km/s/Mpc), and a cosmic opacity of 1.0 (Madau (1995)).

2.1.2 χ^2 Fitting

The method used by SEDfit to determine how well a model fits the data is the Chi-Square Fitting method (Numerical Recipes in C (1992)). This method evaluates how well the data corresponds to the expected value(s) by the following formula:

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{y_i - y(x_i)}{\sigma_i}\right)^2, \tag{2.1}$$

where y_i is the value of the data at some point, $y(x_i)$ is the theoretical value of y_i given x_i, and σ_i is the uncertainty associated with y_i. The value of the difference between the data value and the theoretical vale, divided by the uncertainty, summed over n data points gives the value of χ^2. As the theoretical value of $y(x_i)$ approaches the observed data value of y_i, the value of χ^2 will decrease, thus minimizing χ^2 is equivalent to fitting a better model to the data.

SEDfit calculates the χ^2 value for each model then compares the resulting χ^2

values for all models to find the minimum. This minimum χ^2 model is thus the best fit model, and the parameter values (mass, age, redshift, extinction, SFR) are the best fit properties of these galaxies.

For the fitting done with SEDfit on these galaxies; y_i and $y(x_i)$ are the observed flux and the best fit model flux, and summation is over all filters (given by index i).

2.2 Modelling

To model these galaxies, initial assumptions regarding their evolutionary history must be made. Two different model types were used to model these galaxies, one to simulate a quiescent galaxy and another to simulate a galaxy that is still star forming, each making an initial assumption regarding how the star formation history progressed.

2.2.1 Single Stellar Population

The first model of galactic evolution that will be considered is a Single Stellar Population model (SSP). SSP models assume that all star formation occurred at the same time during the formation of the galaxy. The entire stellar population of the galaxy is formed as a single population of stars early in the galaxy's history, then all star formation ceases in the galaxy for the rest of its history; i.e. the galaxy becomes quiescent. Though an instantaneous formation of an entire stellar population is not physically realistic, it serves as an initial approximation to model these galaxies as quiescent. For galaxies that are both old and "dead", the galaxy spectrum will closely approximate a SSP spectrum, as the absence of bright, blue stars will result in a population similar to a SSP galaxy.

For SSP models, the SFR is assumed to be zero and the extinction is expected to be near zero. This is because the dust that causes extinction is also associated with the gas source of star formation, as the gravitational collapse of cold dust and gas clouds results in stellar formation. Thus a galaxy with no star formation implies that there is no gas (and the associated dust) for which stars can be formed from, thus no extinction.

2.2.2 Constant Star Formation

The second model type used was a Constant Star Formation model (Cons). Cons models assume that the SFR is constant throughout the history of the galaxy, from formation to its current (meaning, as it is observed today) state. Though in reality various perturbations in parameters (such as dust distribution, mass distribution, galaxy shape, external effects, etc.) will alter the SFR through the galaxy histories, this type of models will approximate a galaxy undergoing star formation.

For Cons models, extinction is expected to be non-zero in these galaxies, since, as stated in he previous section, the presence of extinction causing dust correlates with star formation.

2.2.3 Initial Simulations

Initially, both the SSP and Cons models were run with SEDfit with no parameter restrictions. After the best fit model was found for both the SSP and Cons initial conditions, one hundred iterations of Monte Carlo perturbations were generated to simulate how slight changes in the observed magnitudes affected the best fit values.

For this initial run of simulations, some of the resulting best fit values did not agree with what was expected. For the SSP model, the resulting extinction was found to be approximately $E(b-v) = 0.3$, corresponding to the presence of dust in what should have been a dustless, dead galaxy. The Cons model also had a high extinction, at approximately $E(b-v) = 0.5$. Though dust was expected to be present in this model, values above 0.3 to 0.4 are rarely ever seen in observations, especially for multiple objects separated at intergalactic distances.

The Cons model also had a best fitting value for the galaxy ages at approximately $log(age) = 10.3$, or simply put, approximately 20 billion years old. All currently accepted cosmological models of the Universe have an age of 13.8 billion years (Planck Collaboration (2014)), nearly 7 billion years younger then the supposed ages of these galaxies. Also, the resulting redshifts ($z \approx 2.0$), in currently accepted cosmological models, correspond to an age for the universe of approximately 3 billion years, which is almost 17 billion years less than these simulation ages.

With a high age and extinction, the Cons model is being fitted to be as red as possible. Despite being fundamentally different from the SSP model, the Cons model seems to be emulating the SSP model. A passive galaxy is expected to have a very red spectrum (since only cool red stars should be remaining after star formation is quenched), and the Cons model cannot match this redness without abnormally high amounts of dust and extreme ages.

2.2.4 Priors and Second Simulations

Since some of the resulting best fit parameter values for the galaxies are not physical, priors must be applied to the model parameters to limit the model space to results that are physically real.

Firstly, the age of both models was restricted to be less than $log(age) = 9.5$, which corresponds to approximately 3.2 billion years. This limit was chosen because the gzK_s Selection was used to select galaxies at redshifts between $1.5 < z < 2.5$ where in accepted cosmological models a redshift of approximately 2 corresponds to an age of 3 billion years.

Secondly, the extinction was restricted in both models to match the corresponding expected levels of dust. For the SSP model the extinction was limited to $E(B-V) = 0.0$ to simulate the absence of dust, and the extinction in the Cons model was limited to $E(B-V) = 0.4$ to restrict dust to physically reasonable limits.

Once these priors were applied to the age and extinction parameters, the models were fitted again under the new restrictions.

2.2.5 Neglecting the J and H Filters

Since gzK_s Selection is dependent on the observed magnitude of the g (green-visible), z (near-infrared), and K (far-infrared) filters, information from other filters is not required for selecting quiescent or star forming galaxies. Information from other filters, such as the J and H filters, might be valuable for other reasons, such as determining redshift, masses, ages.

To see just how informative the J and H filters are, the modeling was repeated, except the magnitudes from the J and H filters were omitted from the modelling. The previous priors of $log(age) \leq 9.5$, and $E(B-V) = 0.0$ for the SSP model and $E(B-V) = 0.4$ for the Cons model, were applied to this modelling as well.

Chapter 3

Results

The results of the modelling, as shown in Figures 3.1 and 3.2, depict the fit of the filter magnitudes to the model spectrum and the redshift-$log(age)$ and $E(B-V)$-mass spaces of the model parameters.

3.1 Full Set of Filters

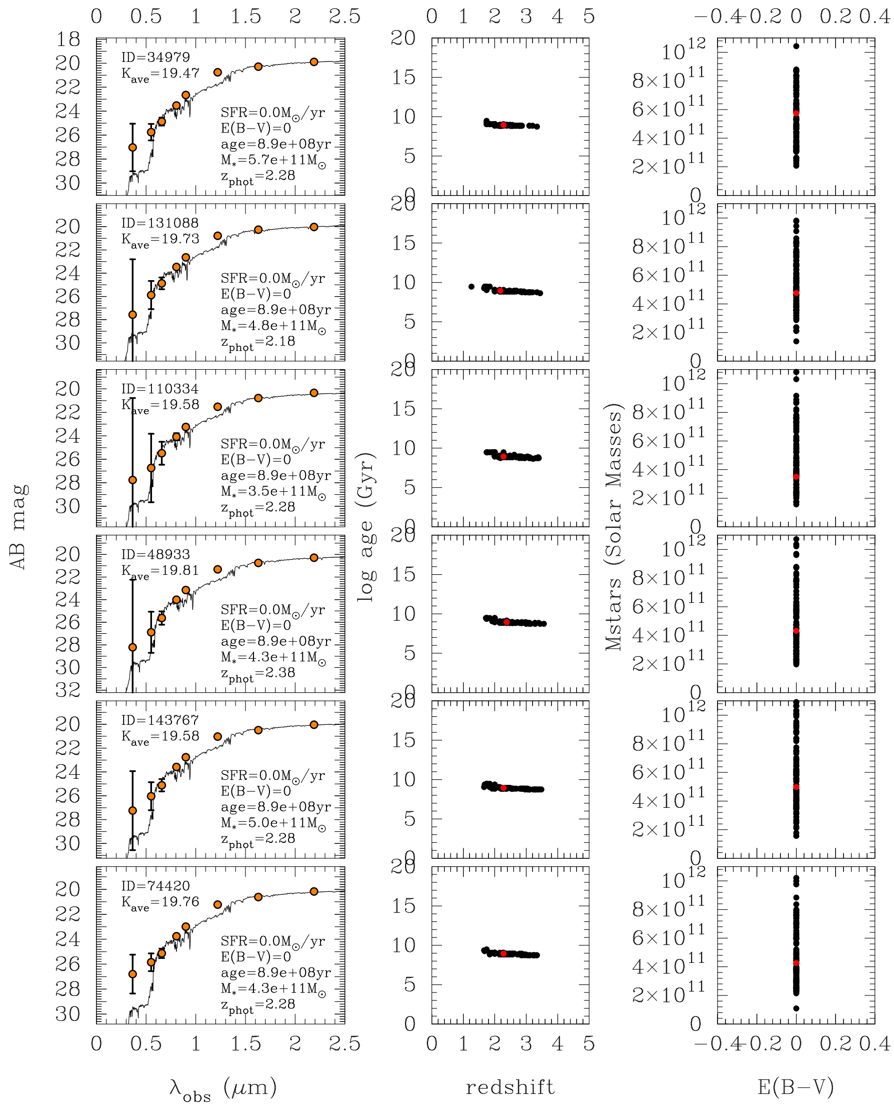

Figure 3.1: Results of the SSP Modelling, Part 1 of 2. First column of graphs are the modelled spectrum and the observed filter magnitudes, as AB magnitude as a function of observed wavelength, best fit values and object ID accompanied in text. Second row of graphs are the results of the Monte Carlo perturbations, graphed as $log(age)$ as a function of redshift, best fit value shown in red. Third row of graphs are the results of the monte carlo perturbations, graphed as mass as a function of extinction, best fit value shown in red.

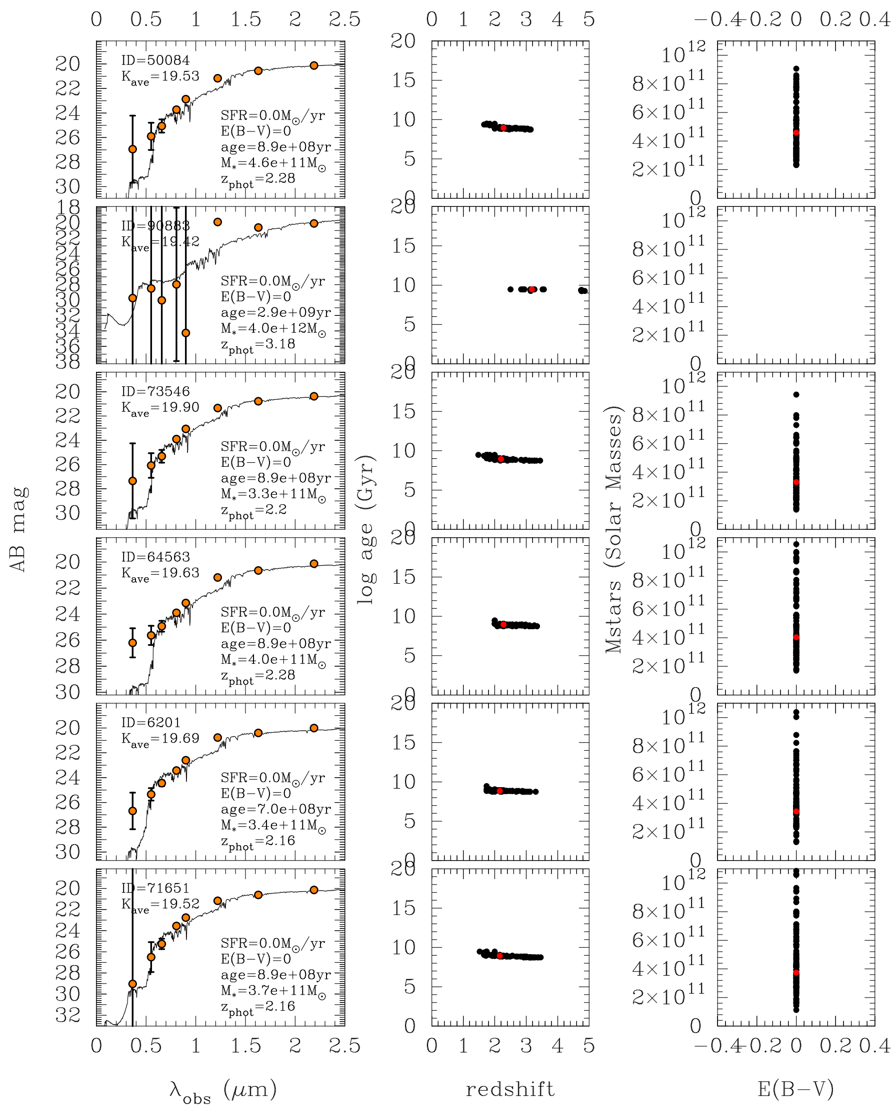

Figure 3.2: Results of the SSP Modelling, Part 2 of 2. Note object 90833 in the second row has large uncertainty in the u, g, r, i, and z filter magnitudes.

One of the objects in this set, identified by ID number 90833, could not be modelled properly due to large uncertainties in the filter magnitudes as can be seen in Figures 3.2 and 3.8. While this object is present in the model spectrums (second row of graphs in Figures 3.2 and 3.8), it is not included in any other graph used below.

3.2 Comparison of SSP-Cons Models

Between the SSP and the Cons models (with the applied piors), the SSP model was found to fit the filter data better than the Cons model, have a lower χ^2 value for the SSP model. Figure 3.3 depicts the comparison of the SSP and Cons model as a ratio of the model χ^2 values, where $\frac{\chi^2_{Cons}}{\chi^2_{SSP}}$ is the ratio. If the models were in agreement with each other, then the ratio between the two would be equal to 1.

For the purpose of whether or not these galaxies are passive quiescent or active star forming, this Chi-Square Fit shows that the quiescent galaxy model is favoured. Modelling agrees that galaxies selected with the PE-gzK Selection Technique are in fact passive quiescent galaxies.

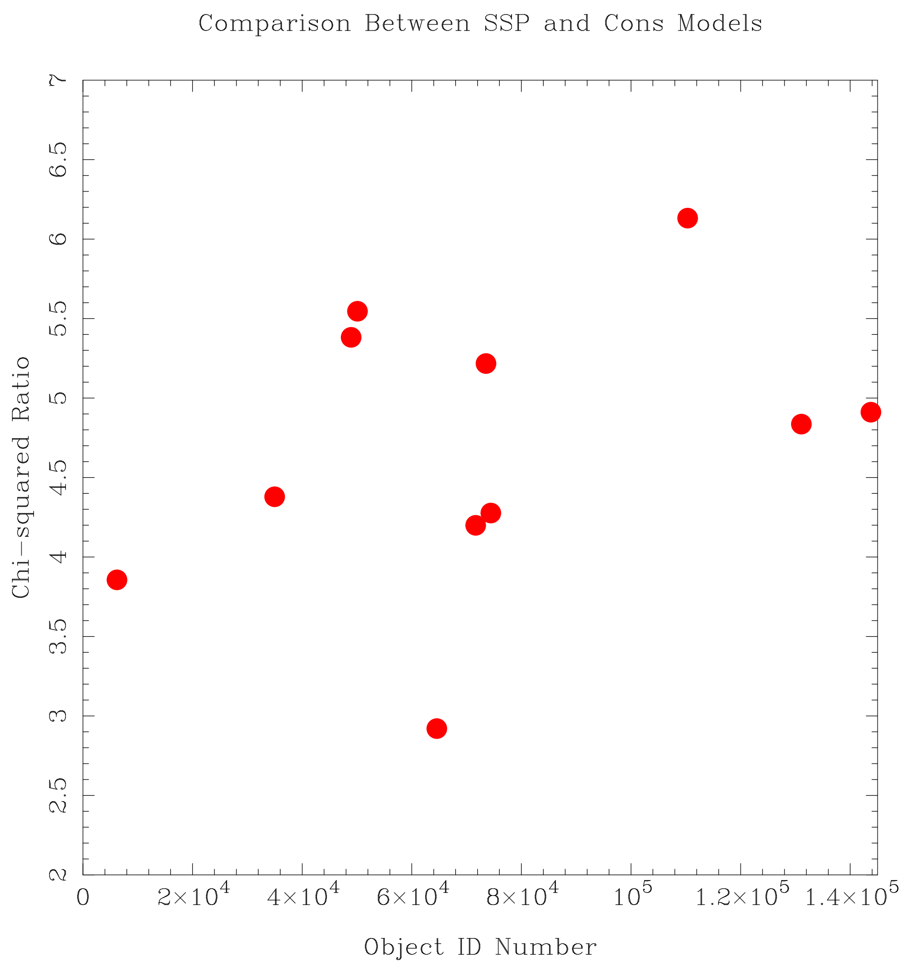

Figure 3.3: Comparison of SSP and Cons Model. Points shown are the ratio of $\frac{\chi^2_{Cons}}{\chi^2_{SSP}}$ for each object. If the two models resulted in identical fits, the points would form a line at $\frac{\chi^2_{Cons}}{\chi^2_{SSP}} = 1$. Since the points are above this line of unity, the χ^2 values for the Cons model are greater than the χ^2 values for the SSP model.

3.3 Galaxy Properties

From the best fit SSP model, the masses of the galaxies were found to be approximately 5×10^{11} Solar Masses (Figure 3.4), the ages of the galaxies were found to be approximately $log(age) = 8.95$ (or 890 Million Years) (Figure 3.5), and the redshifts of the galaxies were found to be approximately $z = 2.3$ (Figure 3.6). Both the extinction and the SFR of these galaxies was found to be zero, by virtue of the definition of a quiescent galaxy.

From the results shown in figures 3.4, 3.5, and 3.6; the best fit model agrees with the gzK selection that these objects are in fact quiescent high mass galaxies from the early history of the universe, with masses on the scale of $5 \times 10^{1}1$ solar masses and an age on the scale of a Gyr at a high redshift of $z \approx 2$.

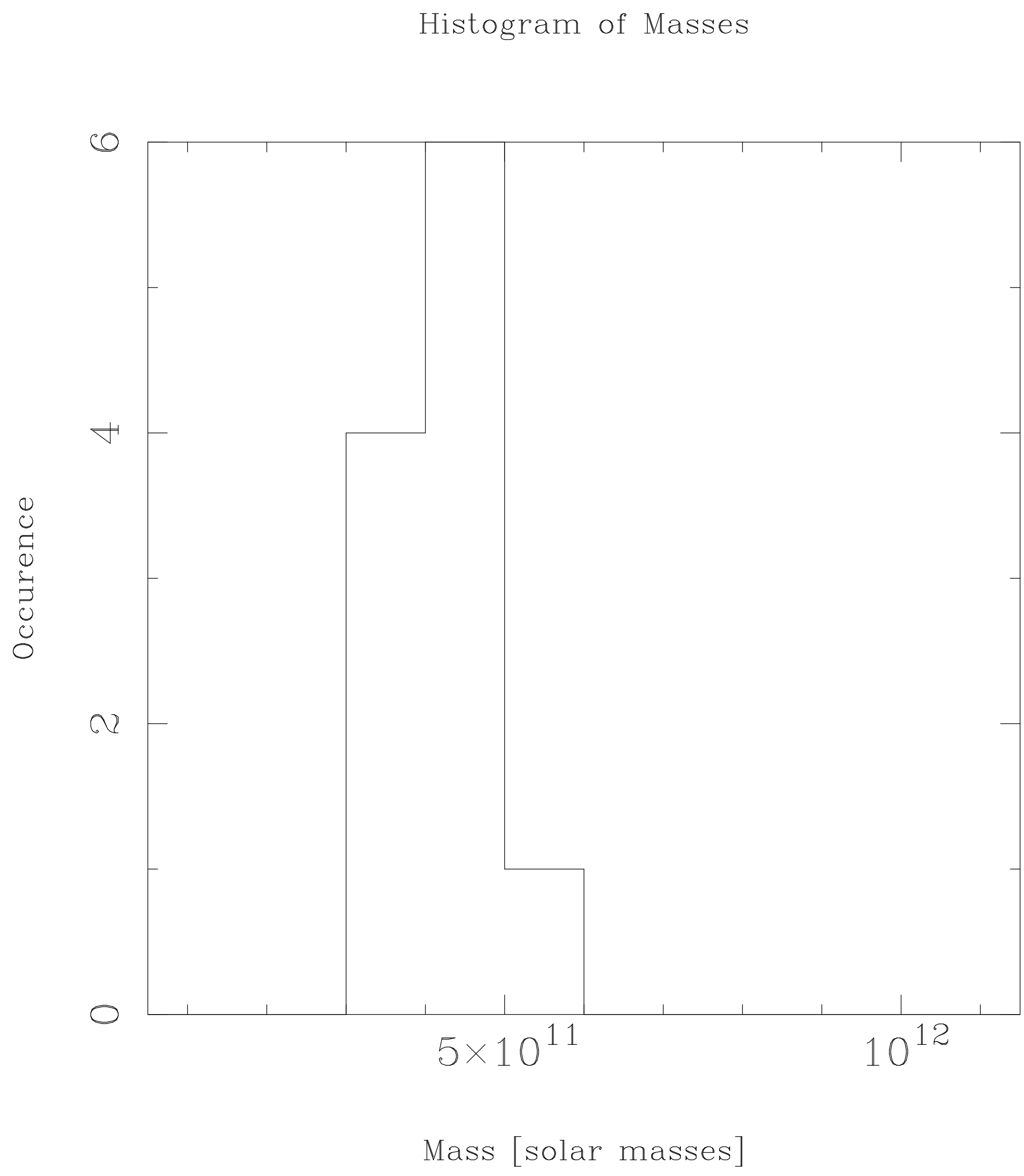

Figure 3.4: Histogram of Masses

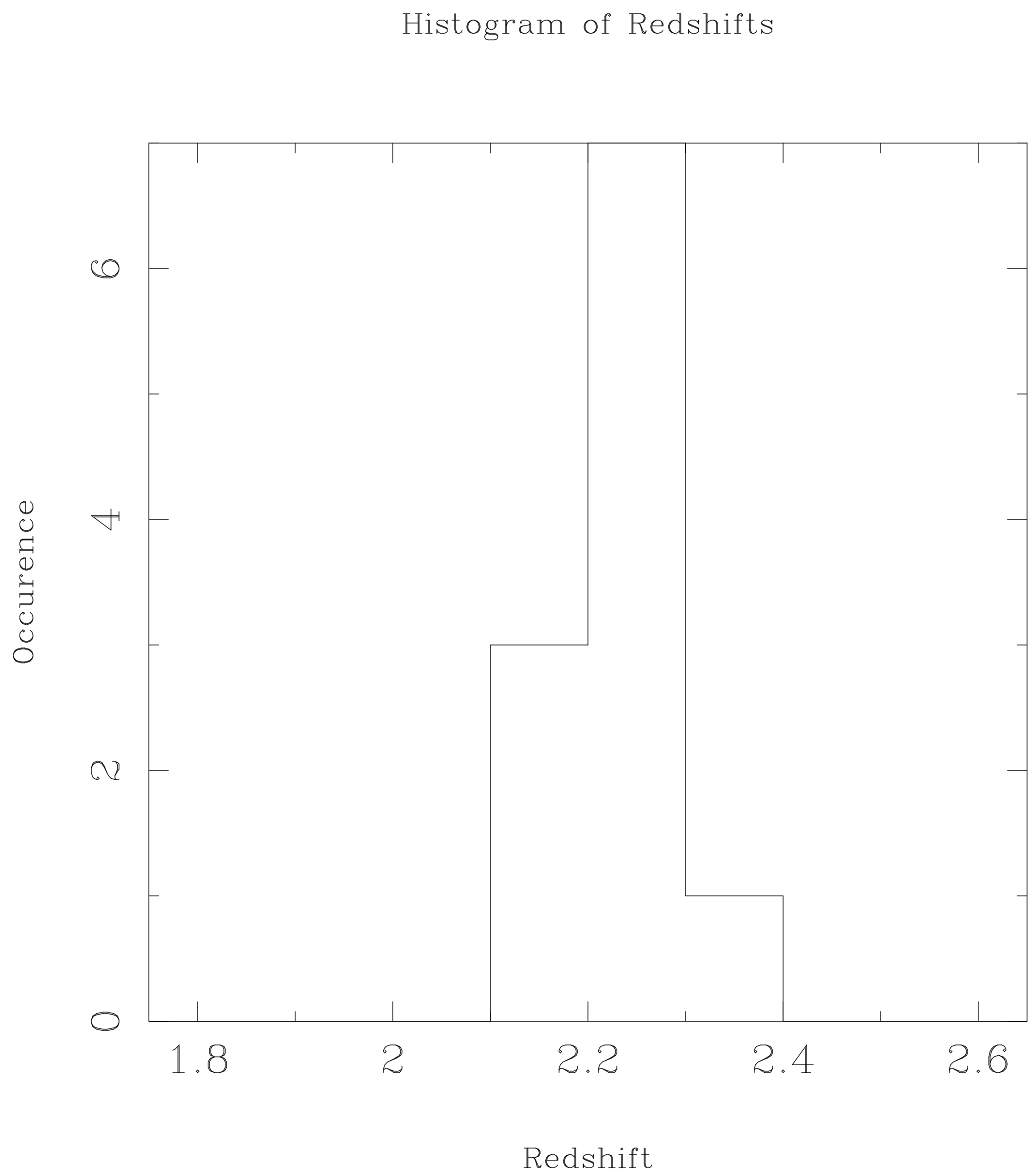

Figure 3.5: Histogram of Galaxy Redshifts

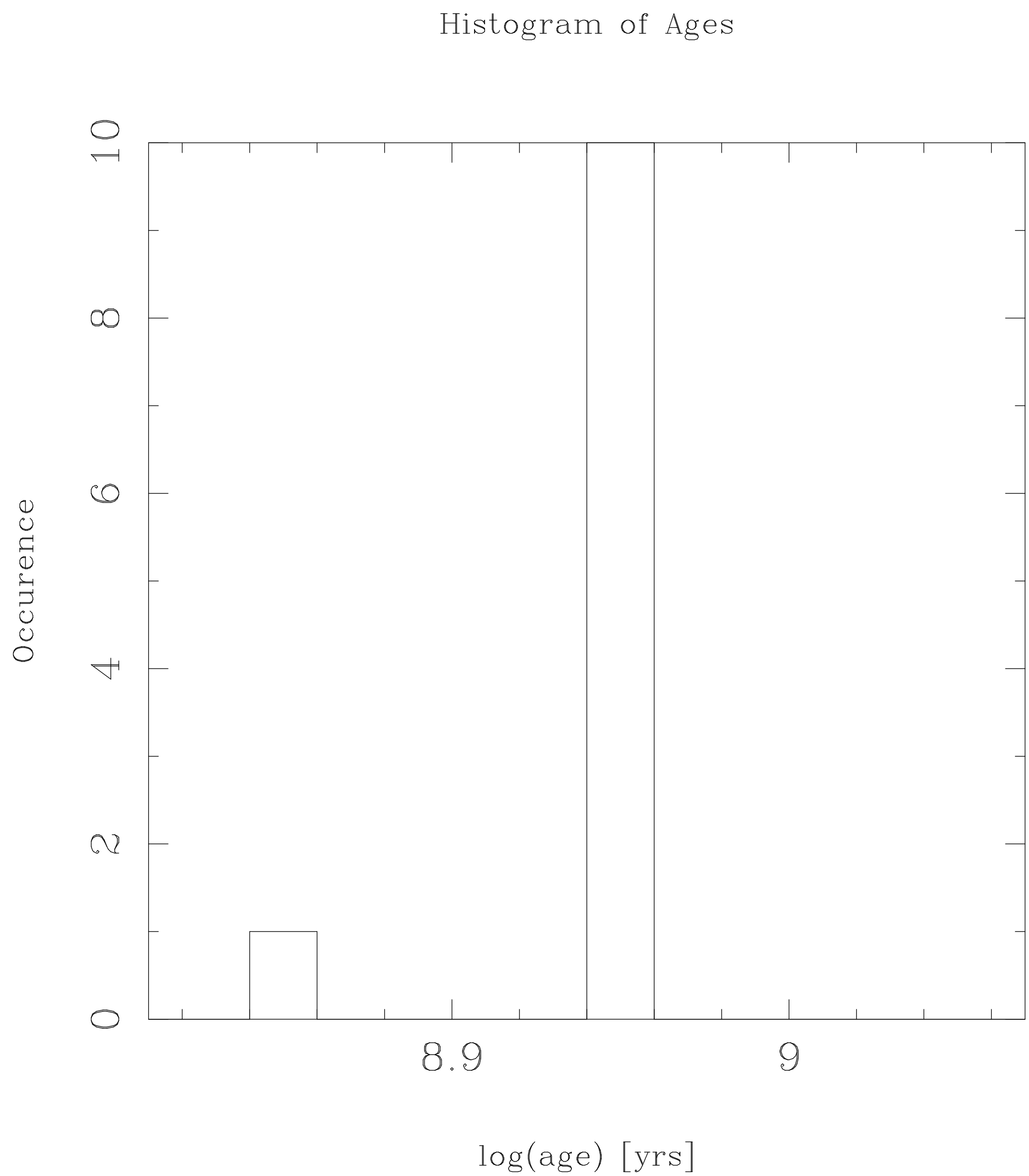

Figure 3.6: Histogram of Galaxy Ages

3.4 Filter Set Without J and H

For the set of filters devoid of a J or H filter, Figures 3.7 and 3.8 show the best fit model spectra:

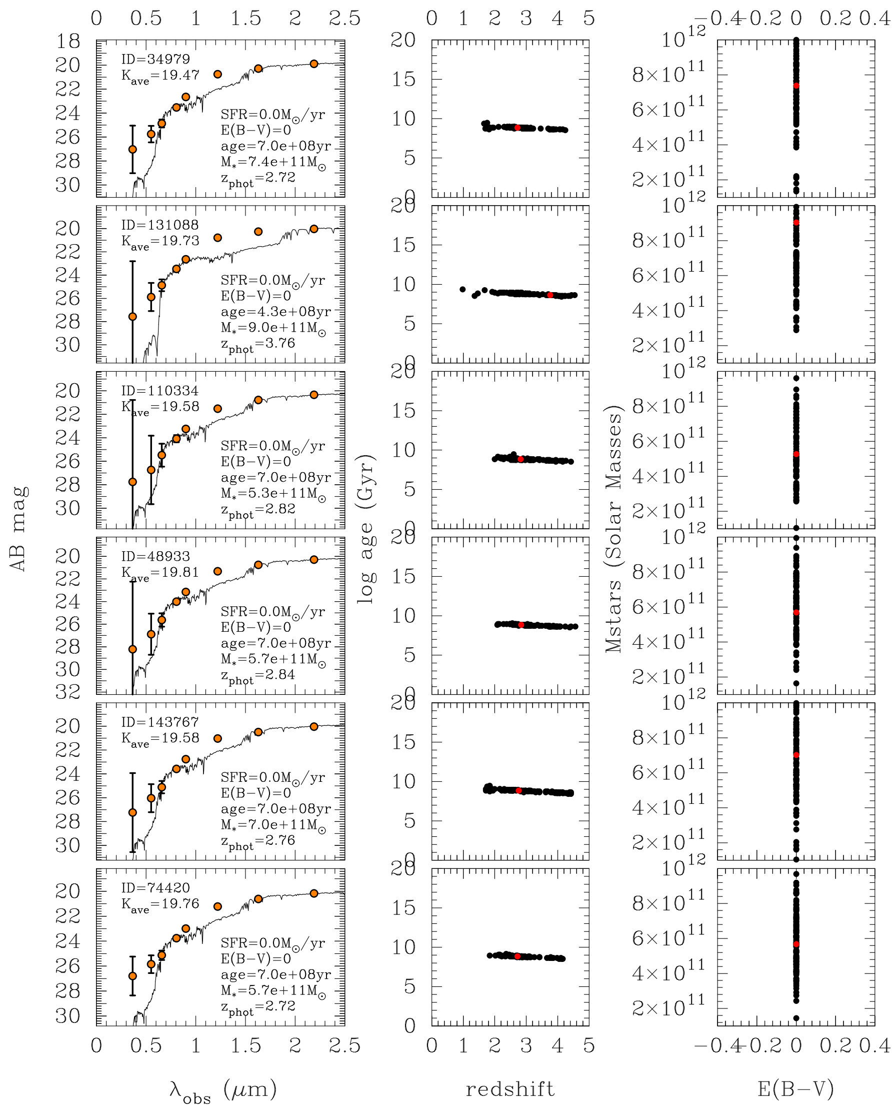

Figure 3.7: Results of Galaxy Modelling without J and H Filters, Part 1 of 2. While the observed magnitudes in the J and H magnitudes are plotted on this graph(and the accompanying second part of this figure), the model spectra did not use these fluxes in the modelling or the fitting.

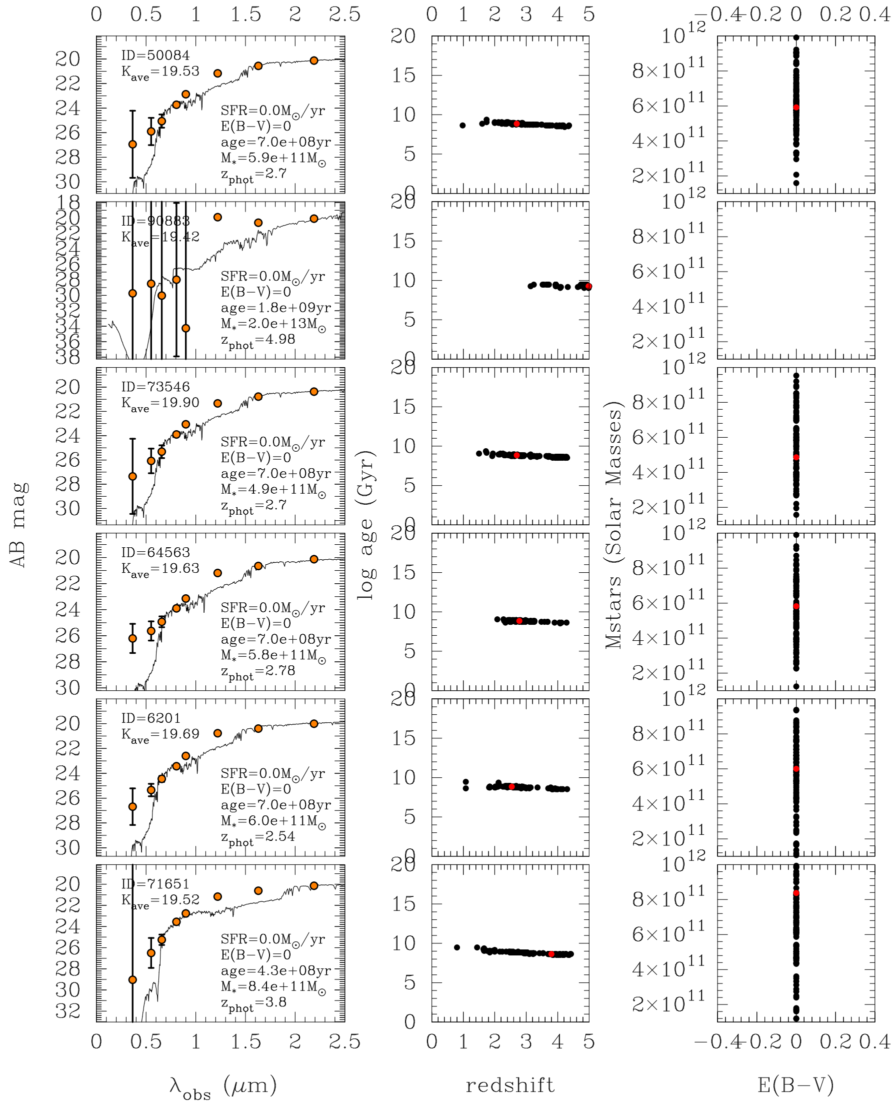

Figure 3.8: Results of Galaxy Modelling without J and emphH Filters, Part 2 of 2. Note object 90833 in the second row has large uncertainty in the u, g, r, i, and z filter magnitudes.

To compare the complete filter set with the filter set missing J and H, the values of mass, age, and redshift were compared between the two model sets. The comparison is in the form of a ratio between the J and H devoid filter set values to the complete filter set values (Figure 3.9) The ratio is in the form of $\frac{X_{noJandH}}{X_{fullfilterset}}$, where X is the data value for mass, age, or redshift. Without the J and H filters, the values for redshift and mass are higher than the values found by the complete filter set, with the masses overestimated by approximately 50% and the redshifts overestimated by approximately 20%. Age on the other hand is only superficially affected by the presence/absence of the two filters.

From the model spectra depicted in Figures 3.1 and 3.2 compared to the model spectra depicted in Figures 3.7 and 3.8, the spectra possess a 4000 Angstrom/Balmer Break, but at different redshifted wavelengths. This illustrates the importance of the J and H filters, as the presence of these two filters in the case of Figures 3.1 and 3.2 have more data points to restrain the wavelength of this feature. Since redshift is calculated by the shift in wavelength of a regular rest frame spectral feature, this means that the presence of these filters constrain the redshift of the galaxies better.

While redshift and mass are overestimated, the degree of which they are overestimated is approximately the same for all cases; redshift averages around 20% with few outlyers near 60%, and mass averages around $60\% \pm 20\%$ with a few outlyers. Thus scaling the value of mass and redshift down by a constant can closely approximate the full filter set. Since redshift overestimates are less than 50%, and since the masses of these selected galaxies is on the scale of 10^{12} solar masses, the lack of J and H filters, while inconveinent, can be accounted for approximately with a simple scaling of the values.

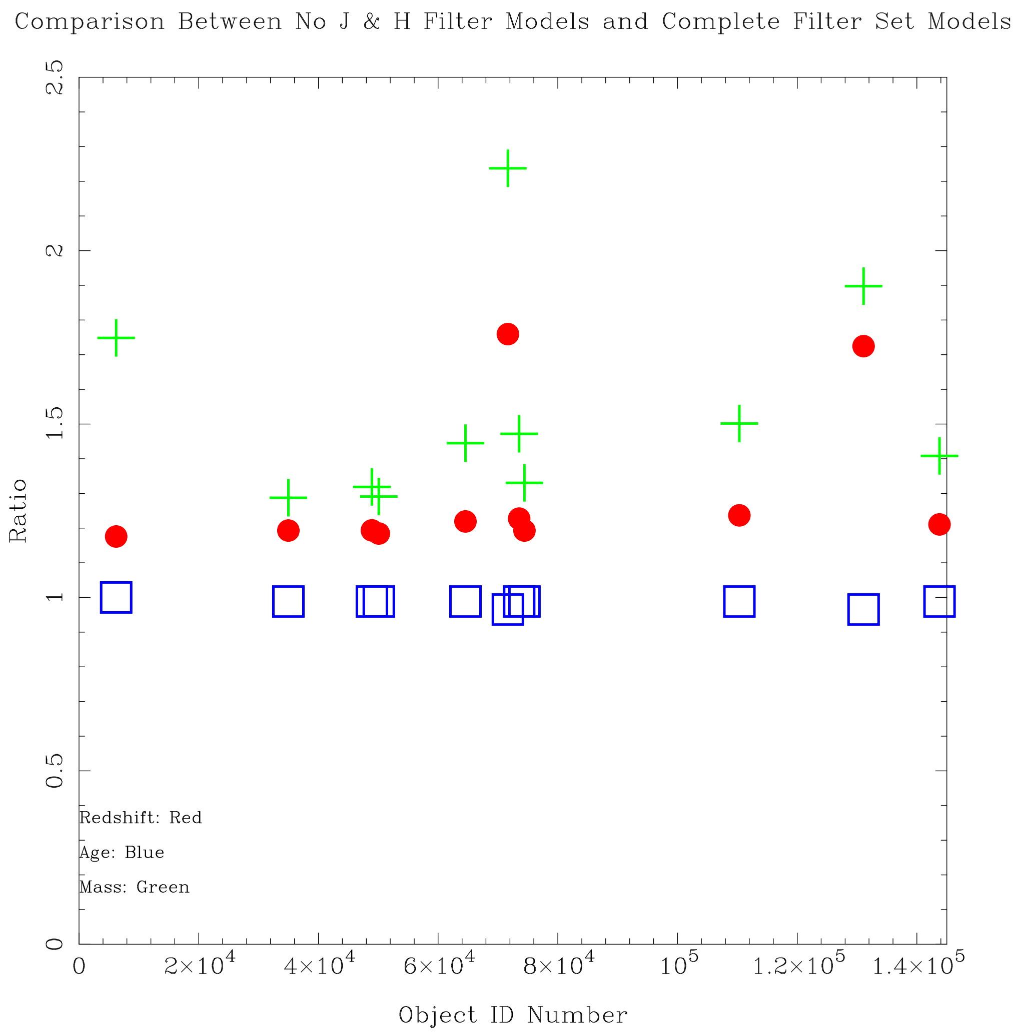

Figure 3.9: Comparison of Full Filter Set to Filter Set without J and H

Chapter 4

Conclusion

From the best fit models, the quiescent SSP models agree best with the filter data, due to a lower χ^2 value compared to the best fit active Cons models. This agrees with the prediction that they were passive galaxies, as these twelve galaxies were selected by the gzK_s Selection Technique to be.

The properties of these galaxies, from the best fitting SSP quiescent model, are: The masses of these galaxies are approximately 5×10^{11} solar masses. The ages of these galaxies are approximately $log(age) = 8.95$ (or 0.89 Gyr) The redshifts of these galaxies are approximately $z = 2.3$, with some spread between $z = 2.1$ and $z = 2.4$. The SFRs and extinctions of these galaxies are all zero, since quiescent galaxies where assumed to have virtually no dust present.

While the model ages were only superficially affected by the presence of the J and H filters, the values of the mass and redshift best fits were changed by the absence of the two infrared J and H filters by approximately 60% and 20% respectively. Though the presence of these filters is helpfull, their absence can be accounted for in approximate by linear scaling.

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