Creating Galaxies

Synthetic Spectral Modeling of Stellar Populations

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Abstract

Synthetic spectral modeling is a technique in which an integrated galactic spectrum is modeled using a library of stellar spectra. In this project we integrate these spectra according to an IMF (Salpeter). For the time-dependence one should ofcourse also use lifetimes for the different phases of stellar evolution. Several approximations are made and discussed to give the reader a feeling about how precise the lifetime estimations are, that are done by comparing our modeled spectrum to three observed spectra. In the end several recommendations are given for a more realistic model, as well as on different methods of galactic age determination.

1 Introduction

In this project we will try to build a model that creates a spectrum of a galaxy at any given age. To do so we will make certain assumptions. In the first place we 'build' the galaxy from a single instantaneous starburst at $t = 0$. Later on we will add starbursts of user-defined stellar masses at user-defined times. The initial mass function (IMF) at any place in the galaxy is defined by the Salpeter mass function throughout the entire life of the galaxy:

$$\xi(M) = M^{-2.35} \qquad (1)$$

To get a spectrum of the galaxy we first take a library of stellar spectra from Fioc & Rocca-Volmerange (1997), see Appendix C. These spectra are extinction corrected spectra of stars with solar metallicity. We decide on which stars are still on the main sequence on the basis of their main sequence lifetimes, taken from Binney & Merrifield using Table 3. After this time they become either a giant (red) or a supergiant (blue) depending on their initial mass. Also for these phases lifetimes are assumed using the same table. After the giant phase we assume the star to be dead: no radiation comes from it at all (remnants do have a very low luminosity, so the expected error is small). On the basis of a comparison between the time at which the spectrum is to be seen and the lifetimes of the different phases for the different stars, the spectra to be integrated are chosen from this library, see also Section 2.3. The spectra are integrated with a weight factor coming from the IMF in order to make sure that the spectra of the less massive stars indeed is radiated by more stars than the spectra of the massive stars.

2 The first starburst

First we 'make' a galaxy of $10^{10} M_\odot$ of stars out of $10^{11} M_\odot$ gas , distributed according to the IMF (Eq. 1). In the very beginning we do not take the effects of gas into account. The Lymann α photons are still there because there is no interstellar gas to transform them into the Balmer and higher lines. These effects will be added later on, as described in Section 2.2. The IDL code used to simulate the spectrum of the galaxy can be found in Appendix A.

2.1 Integrating the stellar spectra

To acquire a spectrum of a whole galaxy we have to take into account all things in the galaxy contributing to this spectrum. One important feature we completely neglect in this project is the dust. Effects of this would be a reddening of the spectrum (scattering is most important for short wavelengths) and of course a total luminosity which is a bit lower than it is now (because you can look less 'deep' into the galaxy, and therefore you would see only the layer of stars at the 'surface'). What the interstellar gas does to the total spectrum is described in Section 2.2. Of course the most important constituents of a galaxy are the stars, so that is what this section is about.

We have to add up several stellar spectra. The stars that are born in the first star burst all have dif-

ferent masses, distributed according to the Salpeter IMF (Equation 1). Stars of different masses have very different spectra (beacuse of their different effective temperatures, surface pressure and so on). We therefore divide the total range of stellar masses in different massbins. For every massbin we calculate the mean mass and we use Table 2 to decide on their effective temperature. These temperatures are an input parameter in the library of spectra and in this way we decide which spectrum is emitted by all the stars in this massbin. To decide how luminous they are we use the same table to find their absolute visual magnitude in the V-band to correct for the normalization used. Furthermore we integrate the IMF from the lower mass limit of the bin tot the upper limit to get the total number of stars in the massbin. To do so we have to use a proper normalization, to be sure that the bins contain the right amount of stars. The total number of stars is given by

$$ N_T = c \int_{0.2}^{200} \xi(M) \cdot dM \qquad (2) $$

where the units of mass are solar masses, and $\xi(M)$ is the IMF (Equation 1). This constant c is to make sure that we have the right amount of stars. We do not know the right amount of stars, but we do know the total mass of the stars: $10^{10} M_\odot$. Therefore we can calculate the constant c by using the equation for the total mass:

$$ M_T = c \int_{0.2}^{200} \xi(M) M \cdot dM = 10^{10} M_\odot \qquad (3) $$

The total number of stars in a massbin is then given by

$$ n = c \int_{\text{lower limit}}^{\text{upper limit}} \xi(M) \cdot dM \qquad (4) $$

The product of the number of stars and their 'unnormalized' spectrum is what is sent out by this particular massbin. We do so for every massbin and add all these up to get the total spectrum of all stars in the galaxy. After this, the effects of interstellar gas can be taken into account.

There are a few problems with this method and it is worth looking at it in order to say something about the constraints on our modeled spectrum. We have to take into account several properties of the available spectra (see also Appendix C). In the first place we can see that our library of spectra will be the most constraining factor. There are just a few spectra available. We made sure that the uncertainty in the fact that you take the wrong spectrum for a certain massbin, is supressed as much as possible by taking almost 4 times as many massbins in

our model than we have spectra for main sequence stars (thereby creating an overlap, several massbins all emit the same spectrum). These 115 massbins are not equally divided along the total range of stellar masses, because a difference of 1 $M_\odot$ is much in the region around 1 $M_\odot$, but it makes almost no difference at masses much higher than that. Therefore we have chosen to divide the first 100 massbins linearly (all with equal sizes) in the region of all stars between 0.2 and 10 solar masses, 10 massbins in the region between 10 and 50 solar masses and the remaining 5 for the stars of 50 to 200 solar masses, which is our upper limit.

We are now able to construct our first spectrum. The spectrum at zero age of a single starburst galaxy without gas (so actually it is more like a cluster) can be seen in Figure 1.
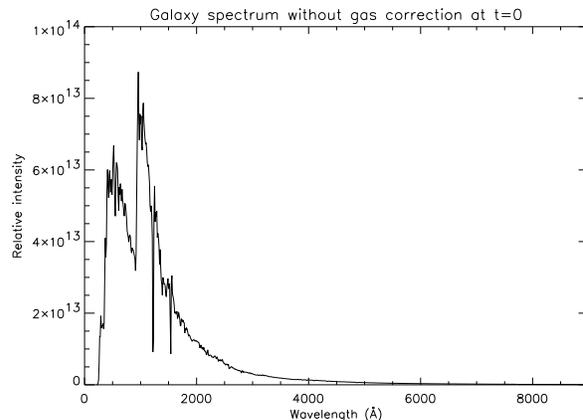

Figure 1: The spectrum of a zero age galaxy without taking the gas surrounding the stars into account.

2.2 The effects of interstellar gas on the spectrum of the galaxy

Our galaxy had a total mass of $10^{11} M_\odot$, so if there is only $10^{10} M_\odot$ of stars formed there is still a huge amount of hydrogen gas (we assume it is only hydrogen) in the galaxy. What will this hydrogen do to the radiation coming from the newly formed stars? Every photon with a wavelength shorter than or equal to the Lymann α wavelength will be absorbed by a hydrogen atom in the ground state, exciting or ionizing it. As soon as the atom falls back in steps, the photons which have wavelengths of a series like Balmer, Paschen etc (higher than Lymann) are very likely to escape from the galaxy (because there is just a tiny amount of hydrogen in a state which can absorb such a photon), while other Lymann photons will most likely be absorbed by again another hy-

drogen atom in the ground state. Therefore, every Lymann photon will be absorbed and redistributed in an empirically known way over the Balmer lines, which will then be in emission (or less absorption than before), see Table 1. The intensity scale in the plots of the spectra is from now on taken logarithmically because of the fact that the emission lines are very strong. This is due to the fact that the massive stars emit a lot of radiation in the UV. All the intensity for the Balmer lines is put in one wavelength bin per spectral line. There is no need to divide them over more because of Doppler shifts (or other line broadening processes), because the wavelength bins are as broad as 6.9 Å. This corresponds to a velocity of 460 km/s, which is greater than the thermal velocity of interstellar hydrogen and greater than the rotational velocity of a galaxy. Therefore any kinematical broadening will have no effect on our spectrum. If we take the effects of the gas into account

Table 1: The interstellar emission line strengths used in our model.

Line	λ(Å)	Relative intensity
Hα	6563	2.85
Hβ	4861	1
Hγ	4342	0.47
Hδ	4102	0.26
Hϵ	3970	0.16
H∞	3646	0.10

the galaxy spectrum will be changed as shown in Figure 2. It is very clear that there are no photons left at wavelengths smaller than the Lymann limit (912 Å) and that the mentioned lines are very strong in emission. This of course is due to the fact that it is a spectrum at zero age. All the very massive stars are emitting lots of UV radiation, which is all redistributed over those 6 lines.

2.3 Time dependence

Of course the spectrum of a galaxy is not constant in time. Stars evolve and so does the spectrum. The lifetime of a star depends mainly on its mass and metallicity. The most massive stars have very short lifetimes, and the less massive ones live longer ($\tau \sim \frac{M}{L}$, $L \sim M^{\sim 3.5}$, so $\tau \sim M^{-2.5}$). Stars with a higher metallicity also live longer. In this project we assume all the stars to be of solar metallicity. Of course there is an error in this approximation. The first stars in a galaxy will have a considerably lower metallicity, but chemical evolution is left out of our model. Lifetimes for the different massbins are taken from Table 3. For
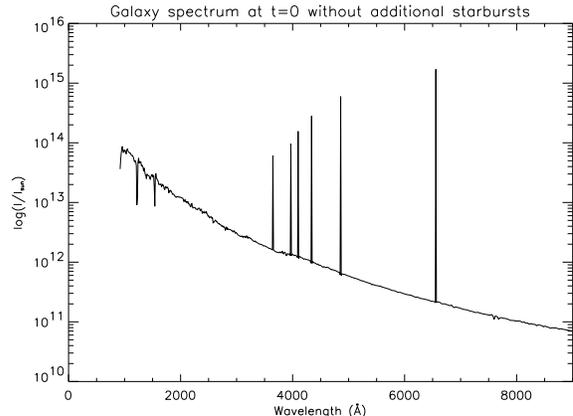

Figure 2: The spectrum of a zero age galaxy taking the gas surrounding the stars into account.

every massbin an average mass is calculated and the closest entry in the table is used. If we want to see the spectrum at time t, and the respective lifetimes are called τ_{MS} and τ_G, then the algorithm takes the absolute magnitudes and temperatures from Table 2. The main sequence (if $t < \tau_{MS}$) or giant columns (if $\tau_{MS} < t < \tau_G$). If $t > \tau_G$ we assume the star to be gone. Possible remnants are not modeled. Remnants have a very small luminosity and therefore they do not contribute a lot to the spectrum of the whole galaxy.

Table 3: Stellar masses and lifetimes for their main sequence and giant phases. All these stars have solar metallicity.

Mass (M$_\odot$)	MS Lifetime (kyr)	Giant Lifetime (kyr)
.2	78245	6651.7
.6	78245	6651.7
1	8899	3590.1
1.5	2471	448.63
2	1030	247.23
3	347.4	119.134
4	171.1	34.747
6	67.92	7.302
9	29.45	2.438
15	12.37	0.983
20	8.46	0.712
40	4.43	0.718
100	1.27	2.136
300	1.27	2.136

We are now able to model a spectrum of a galaxy, whose stars are born in one single starburst, at any age.

Table 2: Stellar masses, temperatures and absolute visual magnitudes in their main sequence and giant phases. All these stars have solar metallicity.

| Mass ($M_\odot$)	MS Temperature (K)	MS M_V	Giant Temperature (K)	Giant M_V
120	52500	-6	47300	-6.2
60	44500	-5.7	40300	-6.4
23	35500	-4.9	34000	-6.6
17.5	30000	-4	29000	-6.7
7.6	18700	-1.6	17100	-6.8
5.9	15400	-1.2	15000	-6.9
3.8	11900	-0.2	12400	-7.0
2.9	9520	0.6	10100	-0.2
2.0	8200	1.9	8100	0.5
1.6	7200	2.7	7150	1.2
1.3	6440	3.5	6470	1.4
1.05	6030	4.4	5850	1.1
0.92	5770	5.1	5150	0.7
0.79	5250	5.9	4750	0.5
0.67	4350	7.4	3950	-0.2
0.51	3850	8.8	3800	-0.4
0.21	3240	12.3	3330	-0.8
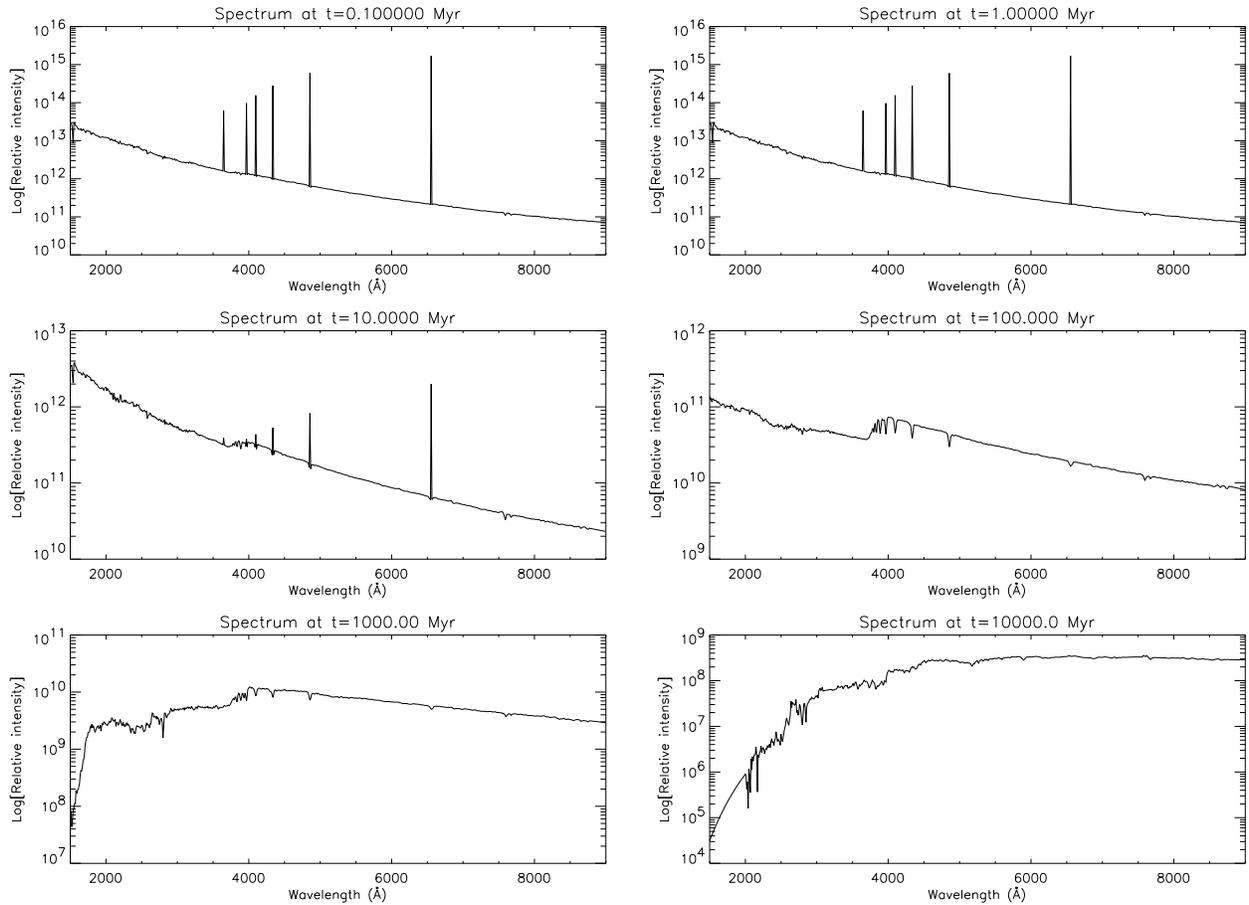
Figure 3: The modeled spectra of a single starburst galaxy at different ages.

2.4 The evolution of the spectrum

We create a galaxy which undergoes a single starburst of $10^{10} M_\odot$, ignoring both further evolution of the galaxy and additional creation of stars. We create different spectra at different times t, which represent different stellar populations.

At $t = 0.1$ Myr and at $t = 1.0$ Myr we see a simple declining slope from short to longer wavelength, with very strong Balmer emission lines. This is a direct result of the, at that time still present, very bright O and B MS stars (sixth image of the MS spectra, see Figure 14 in Appendix C). Since these O and B stars radiate very strongly in the region below 912 Å, gas extiction and re-emission result in very strong Balmer lines and a cutoff below 912 Å in the galactic spectrum.

As these most massive stars have a very limited lifetime, at $t = 10$ Myr we already witness a shift in the galactic spectrum. Most notably the shorter wavelength Balmer lines have become less distinctive, as the less massive ($< 15 M_\odot$) MS stars still radiate strongly in the Lymann continuum region, we see that there still is a strong Balmer α line. We also see that the slope becomes less steep, as is poorly represented by the graph because of the shift in scale. What few blue giants may be present feature a spectrum similar to that of the $15 M_\odot$ MS stars.

At $t = 100$ Myr the Balmer emission lines have completely disappeared as there is no longer Lymann continuum radiation from massive stars. One can now clearly see the Balmer absorption features characteristic of the spectra of $3 M_\odot$ stars, both MS and giant. The peak at around 1500 Å caused by these $3 M_\odot$ stars, has resulted in a slope up at the shortest wavelengths of the galaxy spectrum. One can also find a sort of "step" at around 4000 Å in all spectra representing these ages and masses.

As we enter the dwarf star era we observe even more decline in short wavelength radiation, as can be found in the first 3 graphs of the MS star spectra and the first 4 of the giant star spectra as well. One still finds very faint Balmer absorption lines, as well as an absorption line at approximately 2750 Å, which can be traced back to the $1 - 2 M_\odot$ MS and giant stars as represented by the third graph in Figure 14 and the fourth graph in Figure 15 (Appendix C), respectively. These spectra contain this "step" at around 4000 Å as well.

When stars above solar mass have ceased to exist at $t = 10$ Gyr, we find a spectrum dominant in the visual and longer wavelength range. There's also a strong slope up from around 2000 to 3000 Å in the galactic spectrum, which, with a little difficulty, can also be observed in the spectra of single stars with mass below $1 M_\odot$, note that the plots of the galactic spectra are logarithmic. One can still observe the "step" at 4000 Å, indicating the presence of 0.7 - 0.8 $M_\odot$ stars.

3 Additional starbursts

In real galaxies the stars are of course not born all at the same time, but usually they are formed continously in time. In our simulation we model the birth of new stars as consisting of several distinct starbursts. This of course is a huge simplification of the real situation that brings along some problems. The main problem is the existing of the massive stars. If stars are formed continously there are always massive stars in a galaxy. With several starbursts, however, there are only massive stars in the few years just past the starburst, because these massive stars live so short. The massive stars are responsible for the main part of the ultraviolet radiation because they are very hot, and therefore they are also responsible for the visibility of the Balmer emission lines seen in the spectra before (normally the intensity of these lines are used to determine the star formation rate of a galaxy). Another thing that we do not take into account is the chemical enrichment of the galaxy. Starbursts at later times make stars out of chemically enriched interstellar gas, which therefore have a higher metallicity. That would result in other lifetimes for the stars in other starbursts. With all this simplifications in mind we expand our model to a somewhat more realistic model of a galactic spectrum.

3.1 How to add the second starburst

Instead of continuous star formations we model our spectrum with just one single starburst extra. Although this is a very unrealistic approximation it may give us some insights on how the birth of new stars may affect the spectrum. Later on one can easily expand the model to much more small starbursts in order to approximate continuous star formation. So now we are creating a galaxy which does not have one, but two starbursts. One starburst at $t = 0$ years, and one at $t = 10^9$ years. Again, for both starbursts, we assume an instantaneous creation of all stars, distributed according to the Salpeter mass function (Eq. 1). The first starburst again has a mass of $10^{10} M_\odot$, but for the second starburst we look into various cases with different masses of either 10^7, 10^8, 10^9 or $10^{10} M_\odot$. As stated before, we ignore the chemical evolution of the galaxy, and also the birth of new stars, apart from the two starbursts. Due to these simplifications, our model actually re-

verts to adding the spectra of two different starbursts (without the effects of interstellar gas) together, of which one has a temporal delay of 10^9 years, and then taking the effects of the interstellar gas into account afterwards. The creation of the starbursts themselves is identical to the way they were made in the single-starburst galaxy (SSG).

After creating the spectrum of a double-starburst galaxy (DSG), we take a look at the way it evolves in time, and compare the various cases to each other and with the single-starburst case. The resulting spectra can be seen in Figures 10, 11, 12 and 13 in Appendix B

3.2 Evolution of the spetrum

The evolution of the DSG is obviously exactly identical to that of the SSG until $t = 10^9$ years, when the second starburst goes off. The first difference you will notice between the DSG and the SSG at $t = 10^9$ years, is the influence of the massive stars which are present due to the second starburst. Not only does the DSG have more radiation in the lower-wavelength region, but also the Balmer emission lines have reappeared.

When comparing the DSGs with different masses in their second starburst, Figures 10 and 11 show that at a mass of $10^8 M_\odot$, the spectrum begins to take the shape of a SSG at $t = 0$ again. If we take a second starburst of $10^9 M_\odot$ the shape is almost exactly the same as that of a SSG at $t = 0$, and when we take one of $10^{10} M_\odot$, not only the shape, but also the intensity of the spectrum becomes stunningly comparable to that of a SSG at $t = 0$ years. This is not surprising since we are basically just adding up two galactic spectra here. Whenever the intensity of a SSG $t = 0$ years exceeds that of a SSG at $t = 10^9$ years, the spectrum of the second starburst becomes dominant. For lower masses this is only apparent in the lower-wavelength region, but as the mass increases, the effects become significant in regions of lower energy. Because the overall luminosity of the first starburst has become about 2-4 orders of magnitude weaker over a timespan of 10^9 years, the second starburst becomes completely dominant when it has a mass of the order of $10^9 M_\odot$ or more.

Let's compare our DSG to the SSG at $t = 10^{10}$ years. The first thing that catches the eye is that the shape of the spectra does not differ very much. After all at $t = 10^{10}$ years the first starburst is 10^{10} years old, and the second one $9 \cdot 10^9$ years which is comparable to 10^{10} years. By then, all of the stars with $M \geq 1 M_\odot$ have died, and all of the stars with $M < 1 M_\odot$ are still on the main sequence (that is,

if we only look at the types of stars we use in our model). So the spectrum of a DSG logically reverts to that of a SSG with a mass higher than $10^{10} M_\odot$, and thus has a higher luminosity.

4 Age determination of several galaxies

The next job is to determine the ages of three given spectra. Because the spectra are those of star clusters this immediately implies that the age and metallicity are equal for all the stars in the corresponding spectrum. The star cluster spectra are plotted in Figures 5, 7 and 9 giving the intensities of the ultraviolet-to-visual wavelengths.

Age determination can be done in several ways, see eg. Charlot & Silk (1994) or Schweizer & Seitzer (1998). As a first method photometry is widely used. Color determination from broadband photometry tells you a lot about the age, see for details the mentioned articles. If you have s spectrum you can also determine the age of the galaxy from the continuum shape (as can be seen easily in our modeled spectra) and from equivalent widths of certain spectral lines (eg. Hδ and Ca II H + K). For equivalent width measurements you need a sufficiently high spectral resolution. In our case the spectral resolution of our model spectra is only 6.9 Å and therefore we do not use this method. A second method is called continuum shape fitting. Here you look at the shape of the continuum and sees eg. whether it steepens or not from the violet to the blue range. Of course this method has close connections to the broadband photometry method. Continuum shape fitting is a useful way of measuring the age of a population, but it is not very precise, since one only can fit these by eye and the uncertainties in the age determination will therefore be high. Also the effect dust has on the color of an object makes this method less accurate. Another feature in the spectra which can be used for age determination of young stellar populations are the (relative) intensities of the Balmer emission lines.

Using our synthetic spectral stellar populations model it is possible to give a reasonable estimate of the age of the clusters. The most important aspects of the spectra are the intensities of the (ultra-)violet wavelengths and the Balmer emission lines in the visual range. Balmer lines indicate a star cluster to be much younger, whereas a strong decline in the ultraviolet range implies a much older population, because the only stars in an old population that are still alive are the less massive stars which have their

light emitted in the redder part of the spectrum, as can be seen from our modeled spectra(Figure 3). The three results are summed up below.

Figure 4: NGC 3256 as recorded by the HST. It is a combined image of several optical and (near-)infrared broadband images.
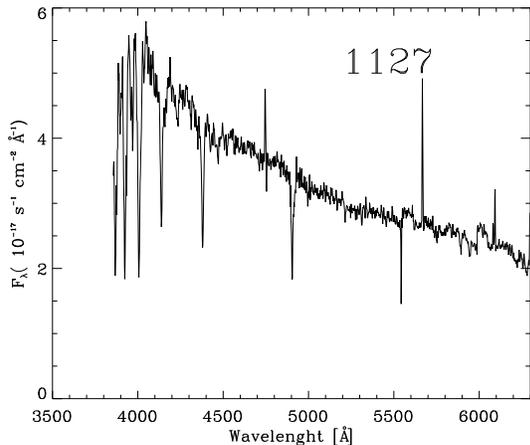

Figure 5: The spectrum of NGC 3256.

4.1 NGC 3256

NGC 3256 can be seen in Figure 4, its spectrum in Figure 5.

NGC 3256 is an intermediate age stellar population. This can immediately be seen by the strong falloff towards the ultraviolet wavelengths; the 4000 Å break is pretty strong. Because the typical Balmer

emission lines are still visible this implies that there are still O and B stars in this cluster. Looking only at the continuum we determine the age of this cluster to be around 500 Myr. There's a small side account: if the Balmer emission lines were not present, the determined age would be different and probably a bit higher. We do not use the Balmer lines as an age indicator in this case.

We can also compare this spectrum to spectra observed before, from clusters in the merger remnant NGC 7252, see Schweitzer & Seitzer (1998). The spectra are very similar except for the Balmer emission lines. For these clusters ages have been derived from photometric as well as spectroscopic methods and they both agree on lifetimes of about 500 Myr, just as results from our models. If we take a look at the image of NGC 3256 we can indeed see clear indications of interacting galaxies, which strengthens the relation between the NGC 7252 and NGC 3256 populations.

4.2 NGC 4038

NGC 4038 can be seen in Figure 6, its spectrum in Figure 7.

Figure 6: NGC 4038 in a composite image, representing more or less real colors, made by a group of a Ohio State University.

NGC 4038 is still very young. It shows high intensities in the violet range and Balmer emission lines in the V band. Close comparison with our model shows that the age is about 1 Myr. The real age value is hard to determine, because in the first few million years the calculated spectra show little to no
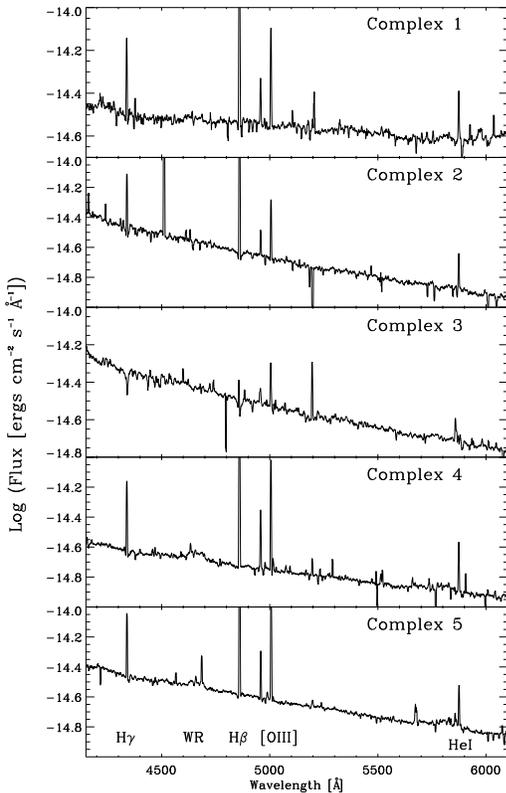
Figure 7: The spectra of the different parts of NGC 4038.

difference.

We can make no comparison of the strengths of the Balmer lines, because we cannot see how strong they are in the observations.

From the optical image it is also clear that this is an interacting system of galaxies, with the majority of the radiation sent out in the blue part of the spectrum. This is a clear indication of the presence of massive stars, and therefore the starburst cannot be more than a few Myrs ago.

4.3 NGC 4365

NGC 4365 can be seen in Figure 8, its spectrum in Figure 9.

Figure 8: NGC 4365 in a composite image, made by combining images in the J and R band, by Princeton University astrophysicists.

The spectrum of the galaxy NGC 4365 shows only little intensity in the violet and blue bands. This implies that the galaxy is very old. The Balmer emission lines have completely disappeared and so we pin the age to 10 Gyr. This is mainly based on continuum shape fitting and a comparison of the width of the stellar absorption lines.

Because spectra are not changing very much anymore around these ages (the stars that are still evolving are evolving very slow) it is very hard to determine a very precise value.

Also here we can take a look at the image to see whether we indeed expect an age that high. It clearly is a very evolved elliptical galaxy. The absence of the Balmer lines has two reasons: there is no ultraviolet
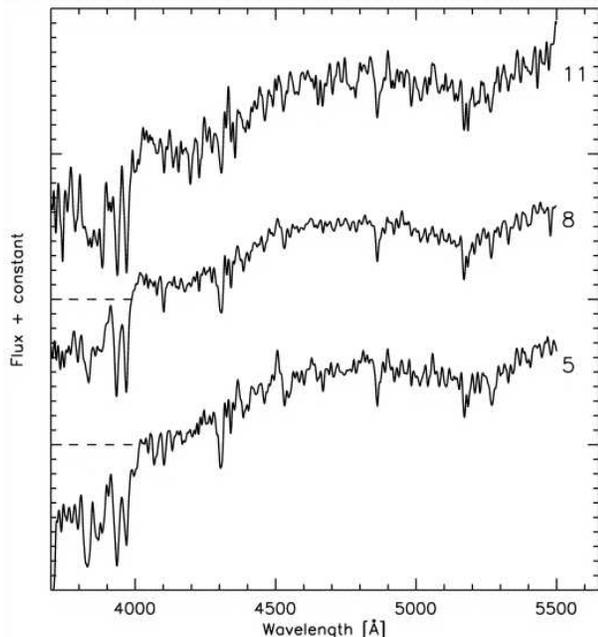
Figure 9: The spectrum of NGC 4365.

radiation and there is no gas. This galaxy will show the same spectrum for a long time.

4.4 Errors in age determination

In all cases the errors involved in the determination of the ages are large. Apart from errors that result from things like metallicity and other problems with our stellar spectra, there are major errors that cannot be underestimated. Just comparing spectra by eye to models is of course not a very good and reliable method. However the fact that we found in literature corresponding spectra, with similar age determinations, improved our feeling that we are not very far from realistic. Also the determined stellar populations showed spectra which appeared pretty much the same as our models, except for interstellar emission lines in young objects, resulting from elements we neglected (such as helium and oxygen).

5 Discussion

In this project a huge number of approximations are made. One even worse than the other. In this section we will investigate what approximations are the worst ones and should be corrected for future use of the code. Also we will try to give a setup for a better age determination method for the observed stellar populations.

5.1 Synthetic spectral modeling of stellar populations

Lots of problems with respect to our model are already mentioned in the according sections. If use of the models comprises merely of determination of age by comparing observations to models, one should of course take the most care of those features of the models for which age determinations are sensitive, see Section 5.2. Here we will discuss only general properties of our model.

As already mentioned the used stellar library (Appendix C) is small and has a bad spectral resolution. A first thing to improve is to use a more comprehensive library. In the library there are only two phases of stellar evolution i.e. the main sequence and giant phases. Everybody knows that after the main sequence phase a star moves across the upper right part of a Hertzsprung Russel Diagram, thereby varying a lot in effective temperature (and hence color) and luminosity. These phases cover a very small part of the star's lifetime, but if you want your spectral model to have a good time resolution the different phases should all be modeled seperately.

In our model we approximated the redistribution process of the Lymann photons as a photon limited process (every Lyman photon was converted into several Balmer and higher series photons). This resulted in a total lack of UV photons below 912 Å. In reality of course there are a few, because, certainly for the stars close to the outer boundaries of the galaxy, this process will be gas limited (optically thin) and there will be some intensity below 912 Å, especially when there are massive stars around. Also the effects of dust should be taken into account, using a proper scattering model.

We used Equation 1 as IMF, which is a nice mean, but is not the real IMF for the whole range of stellar masses we used here. A more accurate IMF for the different parts of the mass range would result in a better division of the total available mass over the stars.

In a future model one should also realize that the method we used (two distinct massive starbursts) is in most cases very unrealistic. In modeling a certain stellar population one should first think about what kind of population one is modeling. If it is a disk galaxy, then star formation is really continuously and one should use continuous star formation in his model or very many small star bursts at time intervals smaller than the main sequence lifetimes of the most massive stars in the model. On the other hand, when modeling a star cluster (stars that are born in one single burst) this is not impor-

tant, and usually there is only a very small amount of gas present after just a short time. Elliptical galaxies are a completely different story. In most ellipticals no star formation is going on anymore, because of a lack of interstellar gas. Such a galaxy consist of stars of which the majority was formed continuously in time, but a non-negligible part is formed in a major starburst at the end (at the time of the merger between its progenitors, if the merging disk galaxy theory of elliptical formation is correct). Depending on the mass fraction involved in this last starburst, its effect on the late stages of galactic evolution (after a few Myr) is visible as the evolution of a passively evolving stellar population.

Our model fits the scenario of the elliptical galaxy best. In these objects the old population is usually *very* old. The evolution of the stars that are still on the main sequence is therefore very slow, and differences in age of less than about 5 Gyrs are not visible. In our model this is represented by the population from the first starburst. The population formed at the merging of the parent galaxies is modeled by our second starburst. Until after a few billion years one can see the effect of this second burst on the spectrum of the elliptical.

5.2 Age determination of galaxies and stellar clusters

If you want to make a modeled spectrum to estimate the age of an observed galaxy or star cluster better than we could do, you can try several approaches. In the first place you can also do spectrophotometric observations, in order to use the color as an age indicator. If you improve the spectral resolution around the most useful spectral lines (say, below 1 Å) in your model and also do spectroscopic observations around these lines with a high spectral resolution, it is possible to get a much better determination of the age, as is shown e.g. by Charlot & Silk (1994) and Schweitzer & Seitzer (1998). Especially combinations of photometric and spectroscopic measurements are useful, because they are more or less independent (if the spectroscopic method is only used for the spectral lines and not for the continuum shape and 4000 Å-break).

Another feature that can be used very well as an age indicator is the 4000 Å break. The ratio of intensities on both sides of the break changes very fast around an age of approximately 5 Gyr, of course depending on metallicities. This method is only useful if the age really is around this 5 Gyr.

Whenever you make an age determination one should bear in mind that ages are extremely sen-

sitive to metallicities, because stars with increasing metallicity are redder and evolve more slowly. Therefore especially photometric color methods are very sensitive to metallicities, but also for spectroscopic methods this parameter cannot be underestimated. An important source of uncertainty in our age determinations are the metallicities of the stellar populations, since our model only contains solar metallicity stars.

References

Binney, J.,& Merrifield,M.I. 1998 (Princeton University Press)
Charlot,S.,& Silk,J., 1994, ApJ, 432, 453
Schweitzer,F.,& Seitzer,P., 1998, AJ, 116, 2206

A The Code

In this Appendix the code is given with which our modeled spectra are created. In the code we used, we ofcourse put the content of eg. FOR-loops a little to the right, but to do so in LaTeX takes a lot of (unnecessary) time, so we decided not to try so here. Also there may still be some commands going on on the next line, without an '&'-sign. This also is an effect of the conversion code-latex.

```
pro ssm

;read the intensities file
masstemperatureflux = fltarr(17,5)
masslifetime = fltarr(14,3)
intensities = fltarr(65,1298)
wavelengths = fltarr(1298)
temperatures = fltarr(65)
MSage = fltarr(115)
Gage = fltarr(115)

currentintensities = fltarr(1298)
inlees = fltarr(5)
dummy = fltarr(5)
dummystr = string(1)

path = ''

;read the mass to temperature to magnitude table from file
close,1
openr,1,path+'mass2t2mag.txt'
for i=0,16 do begin
readf,1,inlees
masstemperatureflux(i,0) = inlees(0)
masstemperatureflux(i,1) = inlees(1)
masstemperatureflux(i,2) = 10^(-0.4*(inlees(2)-4.83)) ;* 4.63e33
masstemperatureflux(i,3) = inlees(3)
masstemperatureflux(i,4) = 10^(-0.4*(inlees(4)-4.83)) ;* 4.63e33
endfor
close,1

;read the mass to lifetime table from file
inlees = fltarr(3)
close,1
openr,1,path+'mass2age.txt'
for i=0,13 do begin
readf,1,inlees
masslifetime(i,0) = inlees(0)
masslifetime(i,1) = inlees(1)
masslifetime(i,2) = inlees(2)
endfor
close,1

;read the spectra file
close,1
inlees = fltarr(6)
openr,1,path+'unordered.txt'
```

```
for i=1,3 do readf,1,dummystr

for j=0,12 do begin
readf,1,dummy
for k=0,4 do begin
temperatures(j*5+k) = 10^(dummy(k))
endfor
endfor

;read the intensities from file
for i=0,12 do begin
for j=0,1297 do begin
readf,1,inlees
wavelengths(j) = inlees(0)
for k=0,4 do begin
intensities(i*5+k,j) = inlees(k+1)
endfor
endfor
endfor
close,1

;reverse the temperatures array to put the main sequence stars in front of the array
;reverse the intensities array for the columns
temperatures = reverse(temperatures)
intensities = reverse(intensities)

nbinslow = 100
nbinsmed = 10
nbinshigh = 5

xstep1 = (10-.2) / nbinslow
xstep2 = (50-10) / nbinsmed
xstep3 = (200-50) / nbinshigh

;create arrays of total mass and of total number of stars per bin
;all values are given in solar units
nbins = nbinslow + nbinsmed + nbinshigh
binmass = fltarr(nbins)
binnstars = fltarr(nbins)

balmerwavelengths = reverse([6563,4861,4342,4102,3970,3646])
balmerratios = reverse([2.85,1,.47,.26,.16,.1])
balmerwavelengthbinnumber = intarr(6)

totalintensities = fltarr(1298,5,6)

;assign temperatures to bins
verschil = fltarr(17,5)
bintemperature = fltarr(nbins)
binfluxcorrection = fltarr(nbins)

;defining the arrays for finding the corresponding spectrum number for every bin
binspectrumnumber = intarr(nbins)
```

```
verschil2 = fltarr(32,5)
verschil3 = fltarr(65,5)

sbmass = [1.e10,1.e7,1.e8,1.e9,1.e10]

;*************do multiple starbursts for different masses
;start a for loop to create different plots for different ages
for sb=0,0 do begin
for dt=5.,10. do begin

;calculate the correct masses and number of stars
for j=0,nbinslow-1 do binmass(j) = (.2+(j+.5)*xstep1)^(-1.35) * xstep1
for j=nbinslow,nbinslow+nbinsmed-1 do binmass(j) = (10+(j-nbinslow+.5)*xstep2)^(-1.35) * xstep2
for j=nbinslow+nbinsmed,nbins-1 do binmass(j) = (50+(j-nbinslow-nbinsmed+.5)*xstep3)^(-1.35) * xstep3

binmass = binmass * sbmass[sb]/total(binmass)

for j=0,nbinslow-1 do binnstars(j) = binmass(j)/(.2+(j+.5)*xstep1)
for j=nbinslow,nbinslow+nbinsmed-1 do binnstars(j) = binmass(j)/(10+(j-nbinslow+.5)*xstep2)
for j=nbinslow+nbinsmed,nbins-1 do binnstars(j) = binmass(j)/(50+(j-nbinslow-nbinsmed+.5)*xstep3)

;create main sequence and giants lifetime for every massbin (all 115)
binstarmass = binmass / binnstars

for i=0,nbins-1 do begin
j = 0
while (binstarmass(i) gt masslifetime(j,0)) do j= j+1
if abs(binstarmass(i) - masslifetime(j-1,0)) lt abs(binstarmass(i) - masslifetime(j,0)) then j=j-1
MSage(i) = masslifetime(j,1)*1.e6
Gage(i) = masslifetime(j,2)*1.e6
endfor

t = double(1.*10^double(dt))

for i=0,nbins-1 do begin
if (t lt msage(i)) then begin ;spectrum creation for ms stars

;find the closest temperature for every bin for main sequence stars
for j=0,16 do begin
verschil(j,0) = abs(binstarmass(i) - masstemperatureflux(j,0))
verschil(j,1) = masstemperatureflux(j,1)
verschil(j,2) = masstemperatureflux(j,2)
endfor

;sort the verschil array
for k=0,15 do begin
for l=k+1,16 do begin
if verschil(k,0) gt verschil(l,0) then begin
h1 = verschil(l,0)
h2 = verschil(l,1)
h3 = verschil(l,2)
verschil(l,0) = verschil(k,0)
verschil(l,1) = verschil(k,1)
verschil(l,2) = verschil(k,2)
```

```
verschil(k,0) = h1
verschil(k,1) = h2
verschil(k,2) = h3
endif
endfor
endfor
bintemperature(i) = verschil(0,1)
binfluxcorrection(i) = verschil(0,2)

for j=0,31 do begin
verschil2(j,0) = abs(bintemperature(i) - temperatures(j))
verschil2(j,1) = j
endfor
;sort the verschil2 array
for k=0,30 do begin
for l=k+1,31 do begin
if verschil2(k,0) gt verschil2(l,0) then begin
h1 = verschil2(l,0)
h2 = verschil2(l,1)
verschil2(l,0) = verschil2(k,0)
verschil2(l,1) = verschil2(k,1)
verschil2(k,0) = h1
verschil2(k,1) = h2
endif
endfor
endfor
binspectrumnumber(i) = verschil2(0,1)
endif

if (t gt msage(i)) then begin ;Spectrum creation for giants

;find the closest temperature for every bin for giants
for j=0,16 do begin
verschil(j,0) = abs(binstarmass(i) - masstemperatureflux(j,0))
verschil(j,1) = masstemperatureflux(j,3)
verschil(j,2) = masstemperatureflux(j,4)
endfor
;sort the verschil array
for k=0,15 do begin
for l=k+1,16 do begin
if verschil(k,0) gt verschil(l,0) then begin
h1 = verschil(l,0)
h2 = verschil(l,1)
h3 = verschil(l,2)
verschil(l,0) = verschil(k,0)
verschil(l,1) = verschil(k,1)
verschil(l,2) = verschil(k,2)
verschil(k,0) = h1
verschil(k,1) = h2
verschil(k,2) = h3
endif
endfor
endfor
bintemperature(i) = verschil(0,1)
```

```
binfluxcorrection(i) = verschil(0,2)

for j=32,64 do begin
verschil3(j,0) = abs(bintemperature(i) - temperatures(j))
verschil3(j,1) = j
endfor
;sort the verschil3 array
for k=0,32 do begin
for l=k+1,33 do begin
if verschil3(k,0) gt verschil3(l,0) then begin
h1 = verschil3(l,0)
h2 = verschil3(l,1)
verschil3(l,0) = verschil3(k,0)
verschil3(l,1) = verschil3(k,1)
verschil3(k,0) = h1
verschil3(k,1) = h2
endif
endfor
endfor
binspectrumnumber(i) = verschil3(0,1)
endif
endfor

;sum up the intensities per wavelength of all the stars in the bins and correct for flambda in solarfluxes (V-
band)
decision = fltarr(nbins)
for j=0,nbins-1 do begin
if t gt (gage(j) + msage(j)) then begin
decision(j)=0
endif
if t lt (gage(j) + msage(j)) then begin
decision(j)=1
endif
for i=0,1297 do begin
totalintensities(i,sb,fix(dt)-5) = totalintensities(i,sb,fix(dt)-5) + intensities(binspectrumnumber(j),i)*binnstars(j)*binfluxcorrection(j)
endfor
endfor

totallymannintensities = 0
for i=0,69 do begin
totallymannintensities = totallymannintensities + totalintensities(i,sb,fix(dt)-5)
totalintensities(i,sb,fix(dt)-5)=0
endfor

;balmerspread = [1,2,5,2,1]
balmerintensities = balmerratios / total(balmerratios) * totallymannintensities

;find the closest wavelength bin for every balmer wavelength
for i=0,5 do begin
minverschil = 1.e30
for j=0,1297 do begin
verschill = abs(wavelengths(j) - balmerwavelengths(i))
if verschill lt minverschil then begin
minverschil = verschill
```

```
minwlnumber = j
endif
endfor
balmerwavelengthbinnumber(i) = minwlnumber
endfor

;add the balmer intensities to the correct total intensities bins.
for j=0,5 do begin
totalintensities(balmerwavelengthbinnumber(j),sb,fix(dt)-5) = totalintensities(balmerwavelengthbinnumber(j),sb,fix(dt)-
5)+balmerintensities(j)
endfor

print,sb,dt

endfor
endfor

;make multiple plots possible in one page
;Plot commands left out.  ;endfor

end
```

B   The double starburst galaxy spectra

Here are the spectra presented of the double starburst galaxies.
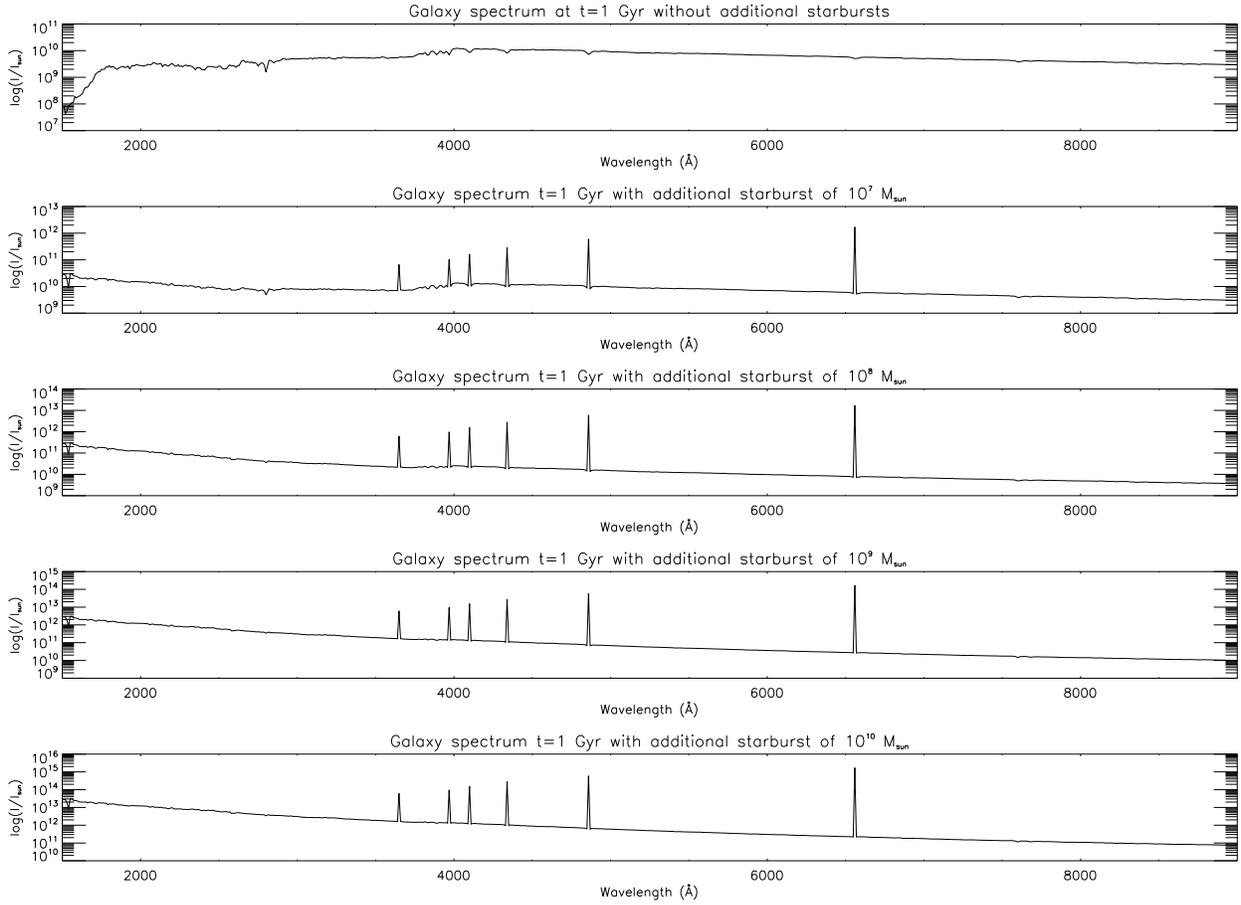
Figure 10: Spectra at $t = 10^9$ yr of a DSG of different masses. For comparison also a spectrum of a SSG at the same age is shown. The second starburst was also at $t = 10^9$ yr.
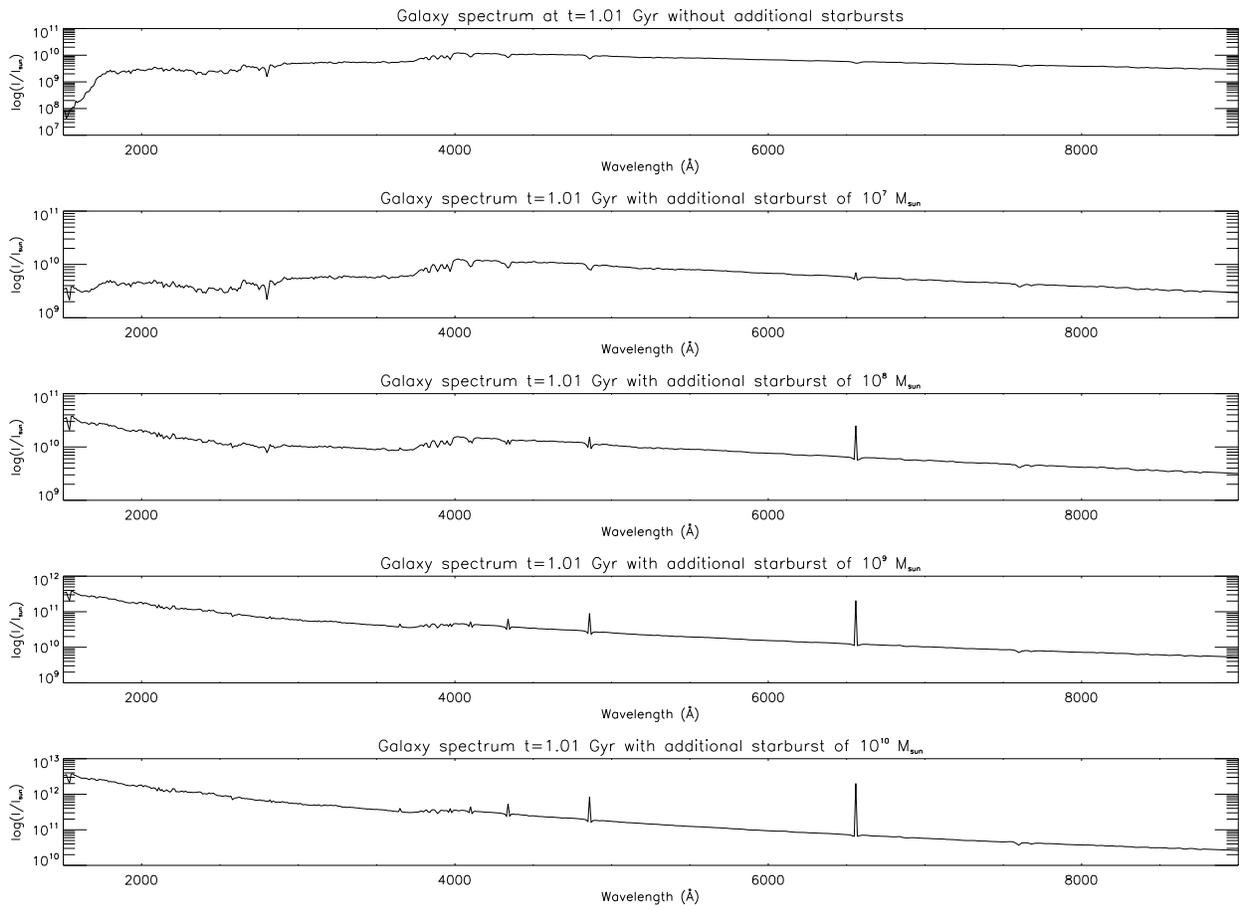
Figure 11: Spectra at $t = 1.01 \cdot 10^9$ years of a DSG of different masses. There is almost nothing changed in the population that was born in the first burst, but the population of the second burst has changed its age 10 Myr. Compare also to Figure 3.
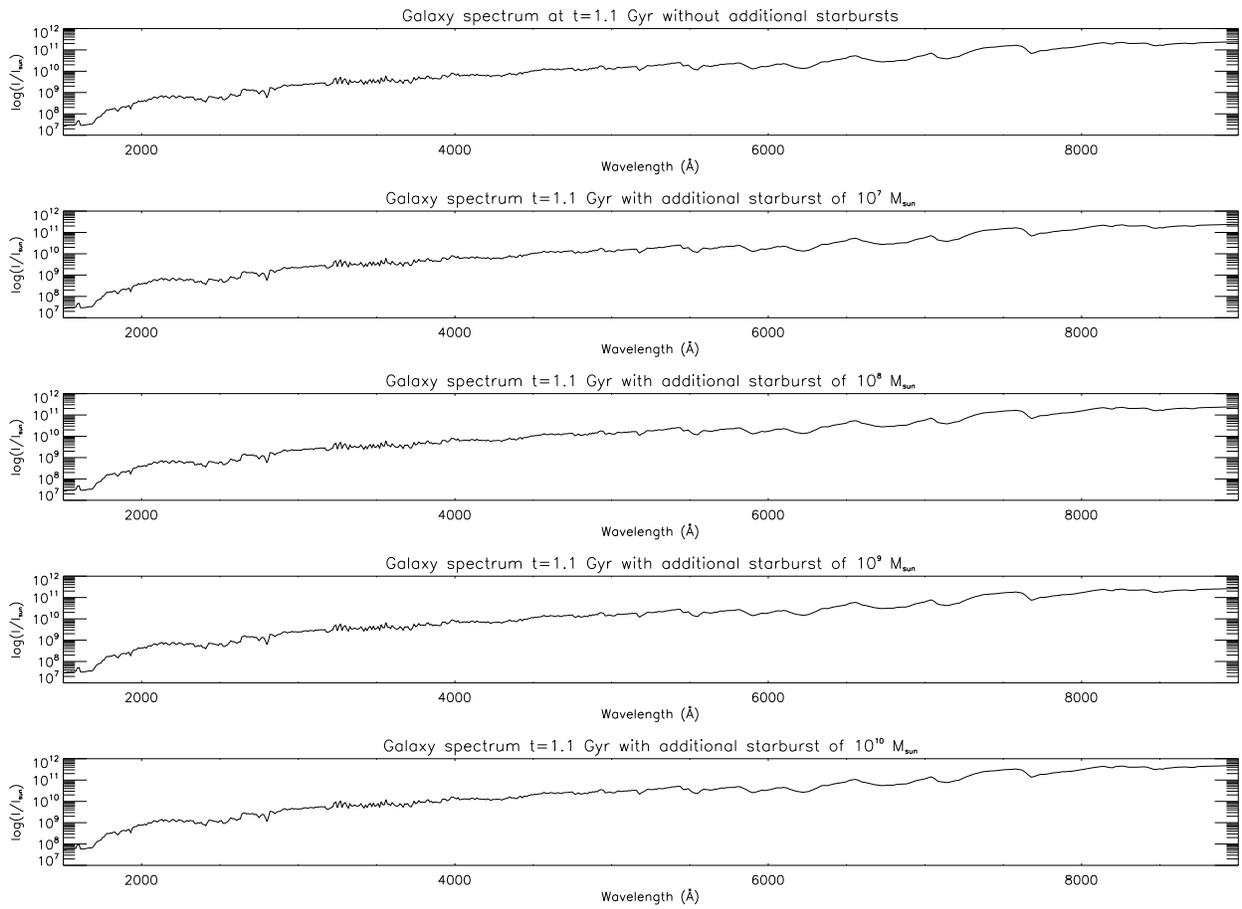
Figure 12: Spectra at $t = 1.1 \cdot 10^9$ years of a DSG of different masses. Here the population from the first burst still hasn't changed that much, but the second spectrum added to it is now like the 100 Myr spectrum from Figure 3.
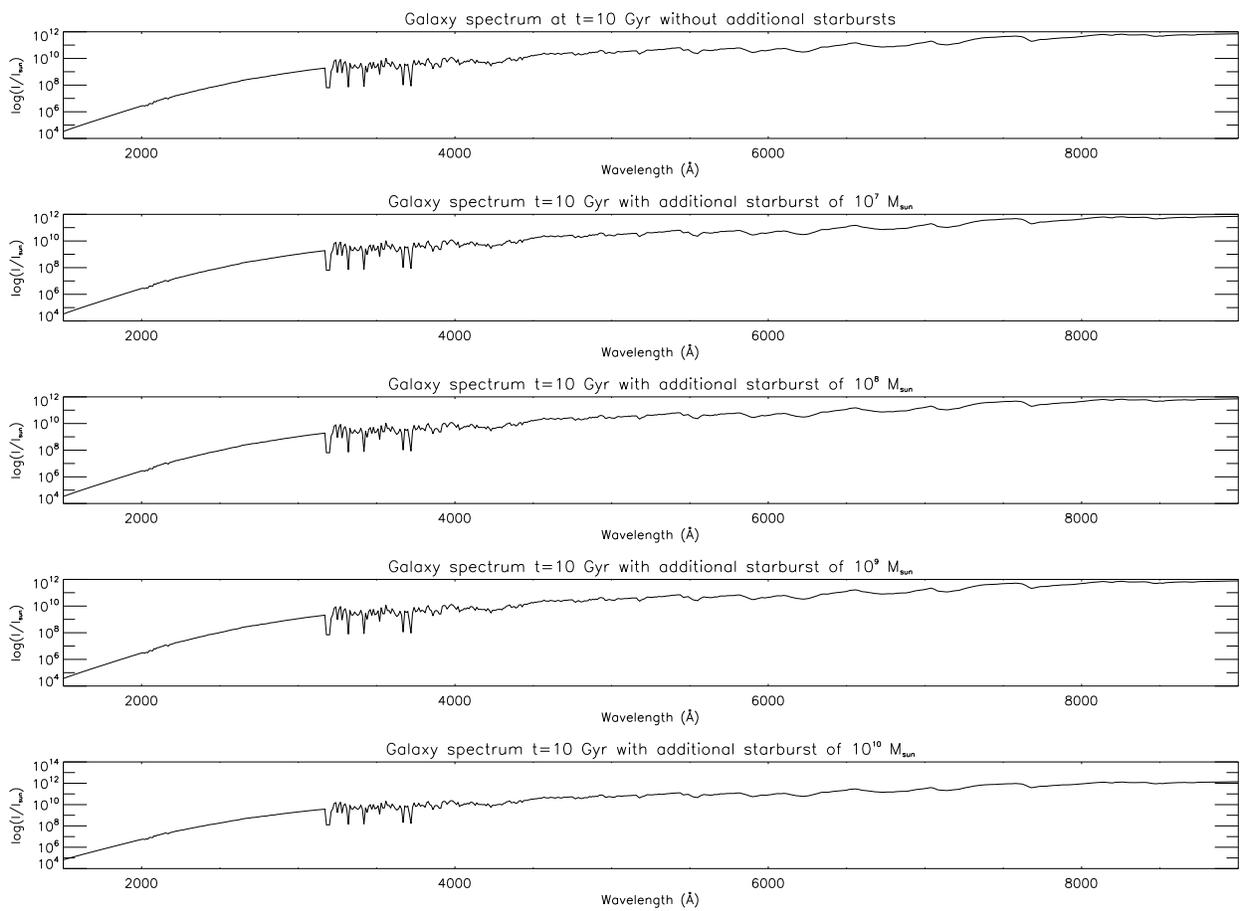
Figure 13: Spectra at $t = 10^{10}$ years of a DSG of different masses.

C The stellar spectra library

The integrated spectrum of the galaxy is simply calculated by adding all stellar spectra there should be at a given time, with the efects of gas added later on. The stellar spectra therefore are an important feature in our project and some remarks have to be made. In the first place the library is small. It only contains 32 main sequence spectra, 30 giant spectra and 3 supergiant spectra. A selection of these can be found in figure 14 for the main sequence stars and in figure 15 for the giants and supergiants respectively. All the spectra are normalized such that $F_\lambda = 1$ in the V-band. Secondly, the wavelength scale is binned in bins of 6.9Å. This is very wide. Therefore we do not have very detailed spectra. In the third place the range of masses for which we have a stellar spectrum is smaller than the range of masses we have in our galaxy. Therefore all the most massive stars emit the same spectrum now (from 120 $M_\odot$ on). The problem is not too big, because there are just a very few of these stars.
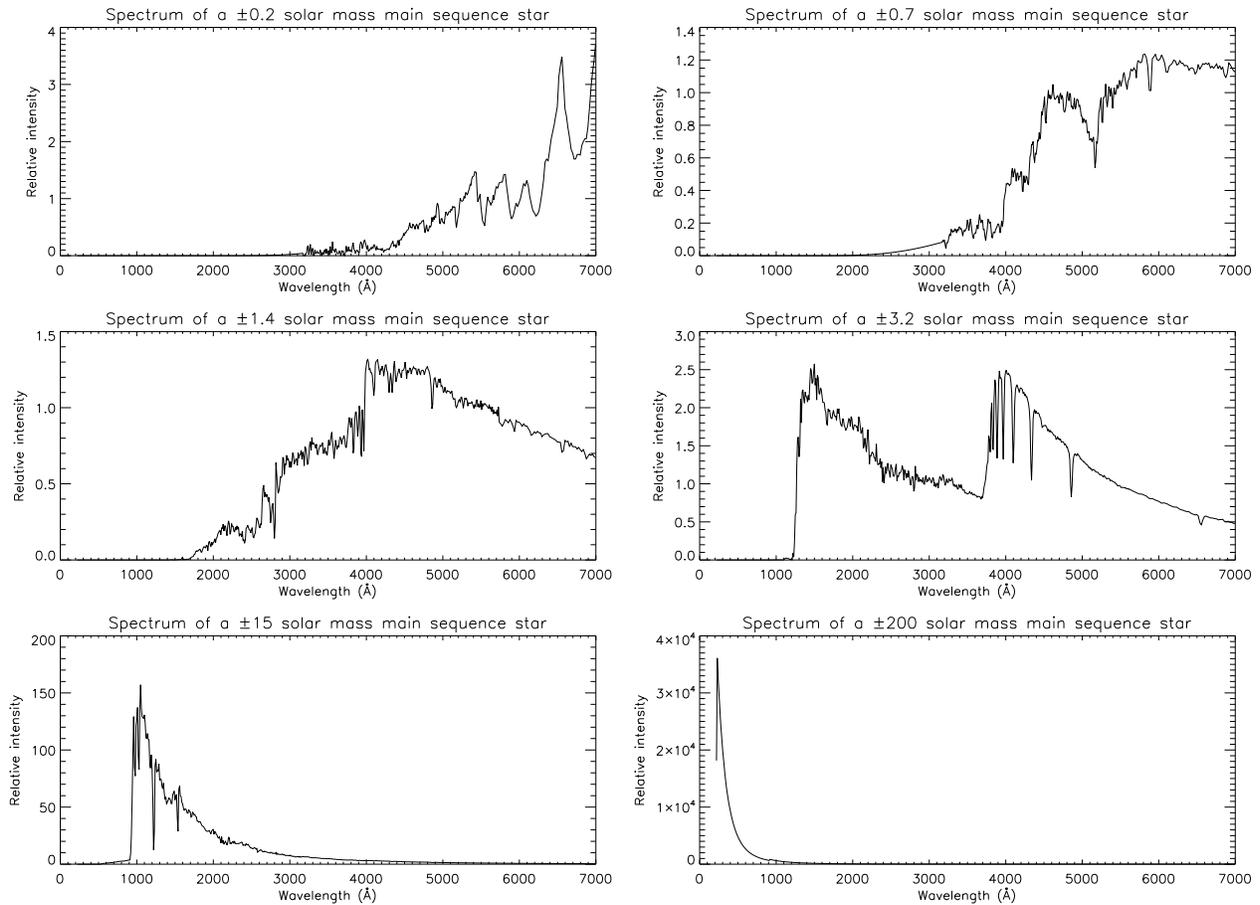

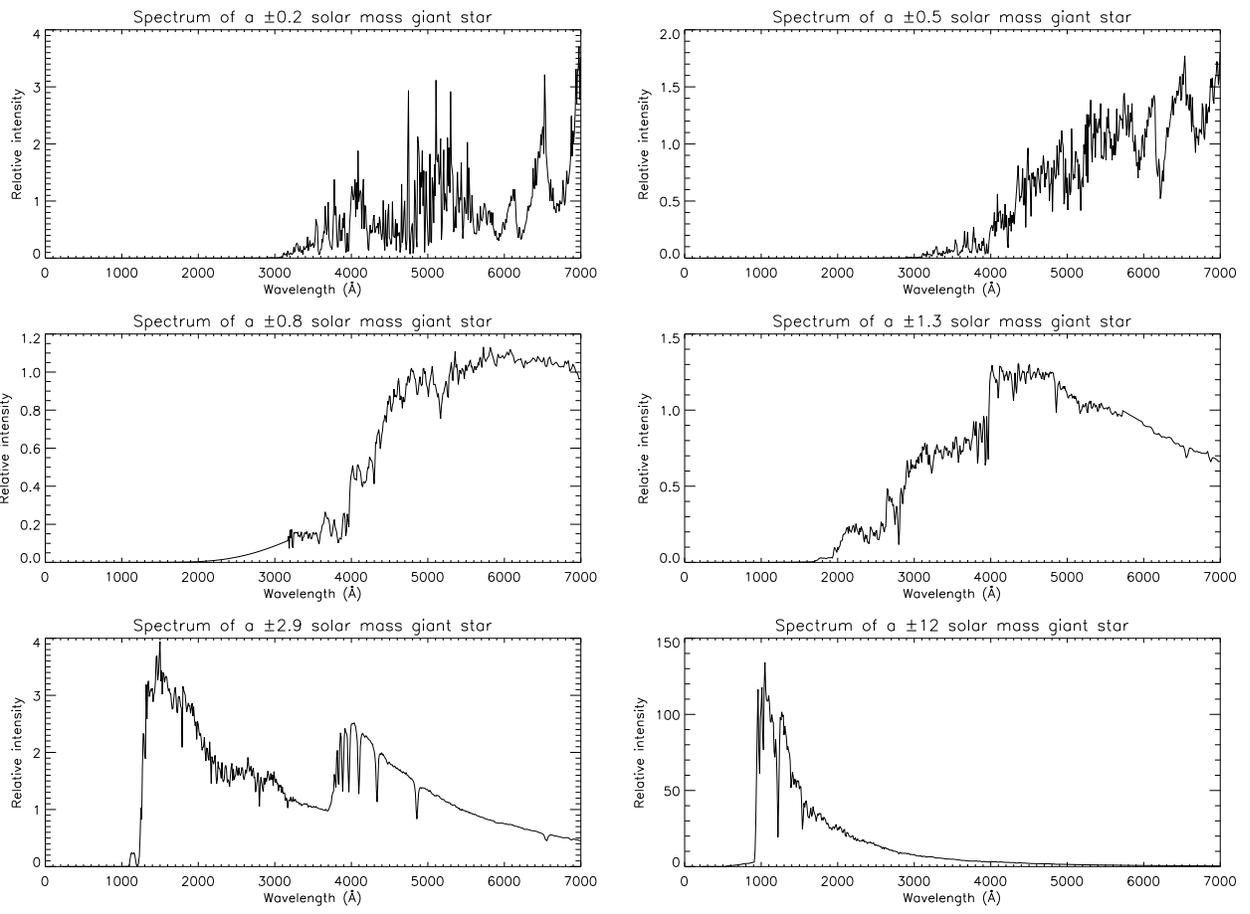Figure 14: A selection of the used main sequence star spectra for a range of stellar masses.

Figure 15: A selection of the used giant star spectra for a range of stellar masses.