

**SED FITTING OF WISE-SELECTED LUMINOUS, OBSCURED QUASARS AT
REDSHIFT ~ 2**

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Abstract

This project was designed to characterize the nature of a sample of high-redshift galaxies selected from the Wide-field Infrared Survey Explorer catalog (WISE), believed to be hosts to active galactic nuclei (AGN). We believe that these objects are highly dust obscured AGN in the center of their host galaxies, at a very interesting and not well understood point in galaxy evolution. After determining the magnitudes of each object in eight different wavelength bands - ranging from the optical to the mid-infrared (MIR) - the absolute fluxes derived from these magnitudes were converted into spectral energy distribution plots (SEDs). A code was developed to fit each of these AGN SEDs to a custom SED template, which could be altered according to an selection of parameters. The templates were a combination of a type-I quasar and a host galaxy, set by the parameters of: the strength of the quasar relative to the galaxy, the amount of dust extinction of the quasar, the temperature of the dust, and the redshift of the galaxy. Through the adjustment of each of these parameters, as well as allowing for the varying of the type of host galaxy, most of the object-SEDs were fit to a template within a reasonable degree of certainty. There were a few objects within our sample which were not well fit by the template, and may require a different kind of template. Throughout this work I will use the naming convention "W####" to describe each of the objects, "W" signifying it is a WISE-selected object and then the first four numbers in its WISE designation.

1 Project Background

Nearing the end of my third year of undergraduate studies, I found myself looking for a research project which I would be able to work on for the summer and possibly as my senior thesis. Interested in large scale phenomena in the Universe - galactic evolution, super-massive black holes, galaxy mergers, etc. - the research being performed by Prof. Mark Whittle, with the assistance of Dr. Ricky Patterson, turned out to be the perfect project.

The research project that I have worked on in this thesis is one aimed at understanding a crucial point in the evolution of massive galaxies. As is a well understood concept in astronomy, the farther away that you look, the further back in time you see, as the light from distant objects has taken billions of years to reach the earth. Therefore the light that we see today is from when the object was much much younger. This fact of nature provides the perfect tool for studying the evolution of galaxies; galaxies at different distances are at different points in the evolutionary cycle. At the cosmic age of 2-4 Gyrs, many of the mechanisms of galaxy formation were working their hardest: there were many galaxy collisions, there was a large amount of star formation, and super-massive black holes (SMBHs) were growing rapidly. The galaxies at this time are thus a fantastic window into these powerful mechanisms of galactic formation and growth.

For this project, the PIs (Prof. Mark Whittle and Dr. Carol Lonsdale) have chosen 15 objects from the WISE survey, characterized by a few key characteristics:

- Red in the mid-IR
- Optically faint
- Strong, compact radio source

These sources hold very luminous - but small - quasars, which are the source of powerful bipolar radio jets, suggested by their compact radio source. The AGN are candidates to be the seeds of the SMBHs which are now at the center of the most massive galaxies. During this cosmic era, both the black holes and their host galaxies were undergoing a period of significant growth and development. We wish to use the data that has been taken on these galaxies to learn key information on this time in galactic development:

1. What is the environment of the host galaxy like? Is the black hole accretion being driven by a gas-rich merger, or by some other mechanism? If it is a merger, what are the masses of the galaxies, and what stage of the merger is it at? How is the cold gas being funneled to the center of the galaxy to feed the black hole?
2. The fact that the radio sources are so powerful yet so compact point to the fact that these are very young, accreting black holes. What are the nature of these jets? Is it possible that the energy from these jets plays a role in "blowing out" the gas from the galaxy and effectively slowing the evolution of these galaxies- a process known as "feedback"?
3. Are these galaxies located in proto-clusters? As these galaxies are thought to eventually form the most massive galaxies in today's clusters, their environment at the time of viewing them may be the elusive proto-clusters.

The data which we have on all of these objects has been obtained from many different sources: the Very Long Baseline Array (VLBA, radio), WISE (mid-IR), and the Large Binocular Telescope (LBT, near-IR and optical). The project is a collaboration of many researchers at different institutions, and I primarily worked with Prof. Whittle.

Object	ra	dec	z
W0204	31.0498564	9.3417482	
W0342	55.5956227	37.891875	0.47
W0404	61.1705733	7.2053501	
W0612	93.0009705	-6.3692208	
W0739	114.78934	23.7946626	
W0943	145.970639	3.0564707	
W1046	161.636733	-2.8418886	
W1210	182.616182	47.8342433	
W1238	189.635611	52.8210063	2.25
W1332	203.128816	79.1178413	
W1521	230.319137	0.2986642	[0.7]
W1703	255.892557	26.2530889	1.08
W1958	299.507186	-7.7692752	1.80
W2331	352.763234	-14.1978387	
W2345	356.421814	31.340515	

Table 1: List of objects in the sample, with both the ra and dec values in units of degrees.

2 Pre-Thesis Work

2.1 Calibrations

Upon joining this project in June 2017, there was not yet fully calibrated data to be analyzed and worked with. All that was presented to me was 15 fields, all of which had either two or four .fits images, in the g, r, J, and Ks bands. These images had already been dark subtracted, co-added, flat fielded, and many had astrometric corrections, however they were still in need of photometric calibrations.

2.1.1 Photometry

Over the course of the summer I began to work with the Image Reduction and Analysis Facility (IRAF) to determine the photometric calibrations for each individual fits image. This is an integral part of determining the observed magnitude of an unknown object in an image. Fits images are made up of a 2d array of pixels, each pixel having a number of counts, called ADUs, which are a direct measurement of the amount of photons which struck that particular pixel. Therefore when one sums up the ADUs in a certain area, they have a true measure of the flux in that area. In order to establish the proper calibration for each image, one uses a list of "standard stars" - stars in the frame which have been previously measured and have recorded magnitudes and errors. Using a task in the IRAF environment called *phot*, one can then measure a relative magnitude for each of these standard stars and compare this to the known magnitude from the catalogs. For our purposes, we used the 2MASS catalog¹ for the J and Ks band images, and the Sloan Digital Sky Survey (SDSS)² for the g and r bands. Through fitting tasks in IRAF, the relation between the true observed magnitude and the one calculated by the IRAF task *phot* was found to be:

$$MAG = MAG_{phot} - zpt \quad (1)$$

Where *zpt* is the zero-point value of the image: an additive number which gives the offset between *phot* calculations and observed values. Through a series of different IRAF tasks, the important relation between ADU and true observed magnitude was found to be:

$$MAG = 25 - 2.5 \log\left(\frac{ADU}{itime}\right) + zpt \quad (2)$$

where *itime* is the integration time of the image. Using this equation, it is straightforward to convert the number of ADUs in an aperture into a real observed magnitude.

2.1.2 Astrometry

Thanks to some lucky timing, the GAIA DR1³ released right near the end of when I was completing the photometric calibrations. Due to the nature of the project, and the interest on the precise

position of the objects, it is very important that the astrometry of each image is as accurate as possible. If the different images of a field are not all calibrated perfectly, we are unable to create RGB images to examine the color of the image, and the radio source will not be properly registered. The GAIA all-sky census provided just the accuracy desired. After the release of this data, I was tasked with re-performing the astrometric fitting on each image. This did not affect any of the work that was done in finding the photometric calibrations, as those depend only on the number of ADUs, not on the exact position of the objects. As astrometric fitting only shifts the images, the overall flux is conserved.

Astrometric fitting is done with a similar concept to the photometry - the measured positions of a group of "standard stars" in each fits image are transformed to match the known positions. This is completed in IRAF, where the central peaks of stars in the image are marked in the xy coordinate system. The coordinates of the standard stars in WCS are then mapped onto the image to overlay on the central peaks in the xy-plane. When this is done, the XY-WCS coordinate conversion of each of the fields which had new GAIA data were made much more accurate.

To see a complete recap of the calibrations, refer to my write-up for ASTR 4993 in the External Links.

2.2 Magnitudes

In order to obtain the magnitudes of each target galaxy in each of the available frames, I would examine the image in DS9 and place a circular aperture over the target galaxy. This aperture gives a lot of information, such as the number of pixels inside, the aperture radius, but most importantly the number of ADU enclosed. From here, it was straightforward to use Eq. 2 to obtain an observed magnitude for each object.

The total errors for these magnitudes came from two errors added in quadrature: the error from calculating the zero-point in the image, and the error associated with the sky background. The zero-point error was output by the IRAF fitting task, and the error from the sky noise was calculated using:

$$\sigma = 1.086 * \frac{\sqrt{\alpha * n_{ap}} * \sigma_{sky}}{ADU} \quad (3)$$

$$\alpha = \left[\frac{(\text{"}/pix)_i}{(\text{"}/pix)_f} \right]^2$$

where α is a scaling factor based on pixel size, n_{ap} is the number of pixels in the aperture, and σ_{sky} is the standard deviation of sky values in a torus aperture around the object, as measured by DS9. The value α is only necessary when there has been a re-binning of an image from one pixel size to another. This method was used to gather magnitudes for each available image in the g, r, J, and Ks bands. Data from further in the IR was found in the WISE database, and covers each of the object in the wavelength bands W1 [$3.4\mu m$], W2 [$4.6\mu m$], W3 [$12\mu m$], and W4 [$22\mu m$] (henceforth the "WISE bands")⁴. All the work done to obtain these magnitudes was imperative to the continuation of the project, and led directly into the work that I completed as my thesis project.

The magnitudes were converted into fluxes [Jy] using the definition for AB magnitudes (Wright et al. 2010⁵):

$$MAG_{AB} = -2.5 \log(F_{\nu}[Jy]) + 8.926 \quad (4)$$

The AB magnitudes for each object can be found below in Table 2.

Field Name Central $\lambda[\mu m]$	g 0.474	r 0.620	J 1.274	Ks 2.163	W1 3.4	W2 4.6	W3 12	W4 22
W0204	23.914 \pm 0.054	23.643 \pm 0.093	INDEF	INDEF	18.020 \pm 0.039	16.382 \pm 0.028	13.933 \pm 0.026	14.028 \pm 0.118
W0342	21.905 \pm 0.009	20.850 \pm 0.200	19.256 \pm 0.014	18.379 \pm 0.024	17.927 \pm 0.039	17.760 \pm 0.047	14.560 \pm 0.040	12.938 \pm 0.060
W0404	27.406 \pm 1.142	26.975 \pm 1.295	22.824 \pm 0.156	21.235 \pm 0.088	19.343 \pm 0.091	18.403 \pm 0.082	15.189 \pm 0.053	13.762 \pm 0.093
W0612	23.164 \pm 0.107	21.819 \pm 0.103	INDEF	INDEF	17.642 \pm 0.046	16.957 \pm 0.035	14.154 \pm 0.033	13.387 \pm 0.084
W0739	24.451 \pm 0.080	24.189 \pm 0.134	INDEF	20.682 \pm 0.062	20.985 \pm 0.384	19.773 \pm INDEF	16.012 \pm 0.125	14.122 \pm 0.186
W0943	24.248 \pm 0.161	23.861 \pm 0.200	INDEF	INDEF	20.283 \pm 0.209	19.309 \pm 0.160	15.369 \pm 0.072	14.135 \pm 0.137
W1046	22.495 \pm 0.015	21.976 \pm 0.018	INDEF	INDEF	19.253 \pm 0.085	17.822 \pm 0.057	15.240 \pm 0.074	13.691 \pm 0.095
W1210	25.530 \pm 0.229	25.121 \pm 0.284	21.965 \pm 0.154	21.810 \pm 0.280	19.613 \pm 0.092	18.301 \pm 0.066	14.836 \pm 0.037	13.696 \pm 0.086
W1238	22.148 \pm 0.018	21.940 \pm 0.022	21.526 \pm 0.078	20.655 \pm 0.112	20.038 \pm 0.132	19.286 \pm 0.136	15.654 \pm 0.073	14.341 \pm 0.162
W1332	24.598 \pm 0.005	24.731 \pm 0.007	INDEF	INDEF	18.257 \pm 0.034	17.131 \pm 0.031	14.646 \pm 0.034	13.810 \pm 0.073
W1521	26.277 \pm 0.529	25.319 \pm 0.425	22.012 \pm 0.158	20.857 \pm 0.142	19.917 \pm 0.130	17.802 \pm 0.055	14.580 \pm 0.033	13.964 \pm 0.093
W1703	22.906 \pm 0.039	22.392 \pm 0.037	21.264 \pm 0.053	20.165 \pm 0.086	18.153 \pm 0.038	16.988 \pm 0.032	14.172 \pm 0.029	13.565 \pm 0.082
W1958	24.754 \pm 0.109	24.358 \pm 0.139	21.997 \pm 0.174	20.631 \pm 0.109	19.350 \pm 0.102	17.929 \pm 0.063	15.185 \pm 0.065	14.054 \pm 0.124
W2331	27.230 \pm 0.047	27.931 \pm 0.038	INDEF	INDEF	19.418 \pm 0.110	18.750 \pm 0.113	15.077 \pm 0.055	13.643 \pm 0.094
W2345	24.087 \pm 0.029	23.835 \pm 0.052	22.142 \pm 0.051	21.335 \pm 0.088	19.261 \pm 0.074	18.498 \pm 0.075	15.259 \pm 0.061	13.556 \pm 0.114

Table 2: Values in this table are given as AB magnitudes, with the value "INDEF" indicating a field in which there was not an image taken. The magnitudes W1, W2, W3, W4, and associated errors were taken from the WISE database.

3 SED Fitting

SED fitting is a process often used in astronomy in which the fluxes at various wavelengths are fit to a model of a full spectrum. The shape that these fluxes take when plotted against wavelength give information that tell of the possible types of objects that are being seen. SED fitting can tell the observer what type of galaxy they are looking at, its brightness, its redshift, and much more information. Over the course of the semester, I developed a code to let the user view and alter customized templates which we believe are characteristic of the types of objects in our sample. Whether or not we were able to match the templates to the observed spectrum told us whether or not we were on the right track, and well matched objects potentially yielded even more information on the physical phenomena inside the galaxy.

3.1 Theory

In order to develop a test template, we first had to establish what it was we think that we were looking at in each object. The idea is that we have many powerful, luminous, obscured AGN which are currently active. The quasar is not thought to be visible in the optical and near-IR, but rather the light is being absorbed by dust which re-radiates this energy as a blackbody. With this in mind, the template spectra must have a few components:

- Host galaxy
- Accreting black hole, possibly reddened by dust (quasar)
- Dust re-radiation

I was then able to think about how to develop the mechanisms behind the code. There are several elements which go into the making of a model, each represented by a certain parameter. First, we must allow for different types of galaxies to be used to make the template. Our AGN sample presumably do not all live in Sb galaxies, and thus galaxy type will be the first parameter (t). Second, we shall have a variable which adjusts the relative strength between the quasar and the galaxy at the g-band (P). This parameter works so that a value of $P = 10$ indicates that the flux of the quasar is 10x that of the galaxy at the g-band. Next, we must factor the dust into the equation and allow for dust extinction (A_V). Dust extinction, also known as reddening, is the number of magnitudes of radiation which get absorbed by the dust. The "V" in A_V signifies that the extinction is in the V-band of the spectra. The dust involved in these objects will be primarily confined to the center of the galaxy, and therefore will mostly obscure the quasar. Thus the only component to which this will apply will be the quasar template.

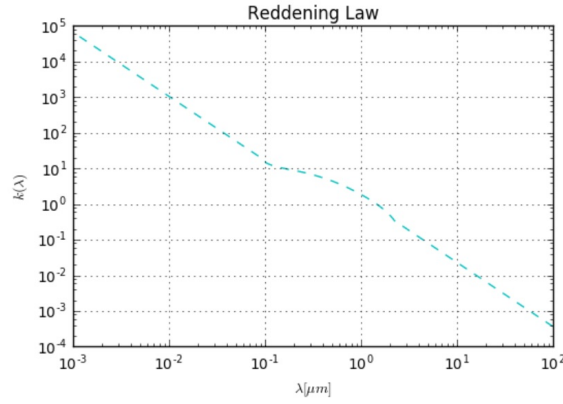
Reddening laws are extremely sensitive to both the size of the dust grains and the wavelength of light being absorbed. Because of this, most reddening laws are established empirically and then

fit using a simple function. The one which we adopted is the Calzetti reddening law (Calzetti et al. 2000⁶), and can be seen below:

$$\begin{aligned} f_{obs}(\lambda) &= f_{int}(\lambda) 10^{-0.4A_\lambda} \\ A_\lambda &= \frac{A_V}{R_V} k(\lambda) \end{aligned} \quad (5)$$

where A_V is the extinction in magnitudes, R_V is a constant, given as 4.05, and $k(\lambda)$ is given by the piecewise function:

$$k(\lambda) = \begin{cases} [2.659(-2.156 + \frac{1.509}{0.1} - \frac{0.198}{0.1^2} + \frac{0.011}{0.1^3}) + R_V] * (\frac{0.1}{\lambda})^{1.8} & \lambda \leq 0.10\mu m \\ 2.659(-2.156 + \frac{1.509}{\lambda} - \frac{0.198}{\lambda^2} + \frac{0.011}{\lambda^3}) + R_V & 0.10\mu m \leq \lambda \leq 0.63\mu m \\ 2.659(-1.857 + \frac{1.040}{\lambda}) + R_V & 0.63\mu m \leq \lambda \leq 2.20\mu m \\ [2.659(-1.857 + \frac{1.040}{2.20}) + R_V] * (\frac{2.20}{\lambda})^{1.8} & 2.20\mu m \leq \lambda \end{cases} \quad (6)$$



The reddening laws that are valid over the wavelength range $0.10\mu m \leq \lambda \leq 2.20\mu m$ are from Calzetti, and the reddening law for larger and smaller wavelengths are a power law extrapolated from the final values of Calzetti's model, consistent with other calculations. These laws, when applied to the quasar template, will yield a new quasar model which is subject only to the one constraint A_V . Varying this value will allow the user to choose how much dust extinction to put into the model. One thing to note: the quasar template which is used in the making of the SED only spans the wavelength range $0.1\mu m \leq \lambda \leq 100\mu m$. In reality, the dust extinction will affect wavelengths much lower than the values in this template. To be self consistent with our model, we thus decided to artificially increase the range of the quasar template to $0.001\mu m \leq \lambda \leq 100\mu m$, while forcing the flux of the quasar to obey the relation that $\nu F_\nu = const$ in the far UV region, from $0.1\mu m$ to $10^{-3}\mu m$.

This reddened quasar model also directly effects the amount of dust that is added into the model. Compared to the un-reddened quasar, the reddened template will have a lower overall amount of flux. This difference in flux must be the same amount which is pumped back out as a blackbody - i.e. the absorbed energy = the radiated energy. The standard blackbody model is given by the Planck function:

$$B_\nu(T, \nu) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \quad (7)$$

However as we are forcing the energy of the blackbody to be the same as the absorbed energy, the only terms which will influence the model will be the terms which involve ν and T . Taking this into account, and switching to λ instead of ν , Eq. 7 becomes:

$$B_\lambda(T, \lambda) = A \frac{1}{\lambda^3} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \quad (8)$$

where the coefficient A in front is the normalizing factor. From this equation, we find our fourth parameter, the dust temperature (T_d). We can now describe the functional model by which our SED template will be made, given as:

$$SED(\lambda) \propto GAL(t, \lambda) + P * QSO(\lambda) * 10^{-0.4A_\lambda} + H(P, A_V)B_\lambda(T_d, \lambda) \quad (9)$$

where

$$P = \frac{QSO(0.474\mu m)}{GAL(0.474\mu m)}$$

$$A_\lambda = A_V * \frac{k(\lambda)}{R_V}$$

$$H(P, A_V) = \int_0^\infty P * QSO(\lambda)(1 - 10^{(-0.4A_\lambda)})d\lambda$$

The parameter P is again defined as the relative strength in flux at the g-band $[0.474\mu m]$ between the quasar and galaxy, and A_λ is defined by the reddening law as in Eq. 5. The dust is written as the normalized planck function B_λ multiplied by the factor $H(P, A_V)$. This is simply the integral computing the change in the flux of the quasar as a result of reddening. By multiplying the normalized B_λ by this factor, we force the energy within the planck function to have the same amount of energy as was absorbed by the dust.

Eq. 9 gives us four parameters to use to make a SED template: t , P , A_V , T_d . However, there is one final variable which has to be included: the redshift of each object (z). When the templates are plotted against the WISE data points, they are forced to be matched on the g-band data point. However objects with different redshifts have their g-band λ shifted by different amounts. The redshift therefore are necessary to know at which wavelength to match the template to. The change in wavelength as a function of z is given as:

$$\lambda_{int} = \frac{\lambda_{obs}}{z + 1} \quad (10)$$

Given an understanding of how these five parameters will affect an SED template, I was then able to continue onto writing a code to develop a customizable template generator.

3.2 Fitting

The final product of this thesis is a Python code developed in the Jupyter environment which allows for interactively fitting each of the 15 objects in our sample to a customized SED template. The user of this code is able to change each parameter described above in 3.1 in order to best fit the 6-8 data points for each object in our sample to a template composed of a galaxy, a reddened quasar, and a blackbody of dust radiation. There are 11 templates used in this code, which were sourced from a Swire galactic template catalog (Polletta et al. 2007⁷), and include:

- Type I Quasar(QSO1)
- Elliptical aged 2Gyrs, 5Gyrs, and 13Gyrs (ELL2, ELL5, ELL13)
- Spiral types 0-d (S0-d)
- M82
- ARP220

It is important to note that this code was not immediately written in its final form. Coming into the semester I had limited experience writing code in Python, and so had to develop the skills along the way. This program was built in pieces to make sure that what was getting coded was scientifically accurate, and thus the templates which were being generated were viable. In the following sections I will describe the overall organization of the code, what each subroutine does, and what the final results are. I will also attempt to give an intuitive explanation of how to use the interactive portion of the code, to allow readers (specifically ones who may work on this project in the future) to fit the WISE objects themselves.

3.2.1 WISE Color Plots

To aid in the fitting of the templates, we utilized color-color plots. Specifically, we used a color-color plot which plots the values of the Vega magnitudes W2-W3 vs W1-W2. As seen below, this

form of color-color plot can specify information about what the object may be, based solely on the spectrum from the range W1-W3.

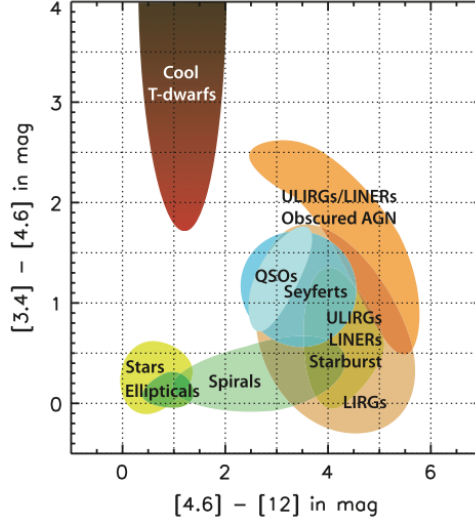


Figure 1: The axis labels refer to the central wavelengths for each of the three involved bands: W1 - $3.4\mu m$, W2 - $4.6\mu m$, W3 - $12\mu m$

Our objects being obscured AGN, their position on this plot should be in the orange area on the right hand side. Indeed when the object's points are plotted they do fall in this area of the graph. What plotting this will help us to do is act as a marker for at least three data points on the template. The difference in magnitudes corresponds to a ratio of fluxes, so by calculating the values of W2-W3 and W1-W2 for each object and the template, we are able to have an extra visual tool to help the fitting process - the magnitude differences give the slope of the SED between the three points on a log-log plot.

3.2.2 Parts of the Code

This code has two main functions: first to take base galactic and quasar templates, along with given parameters, and produce an SED template; second to present the template and WISE data in an interactive plotting environment. I primarily wrote the template-producing code using subroutines, such that each time the interactive plot is used and changed, the code updates the parameters and remakes a template. In this section I will briefly describe the basic setup of the program, as well as the individual subroutines which are called. The code blocks referenced can be found in Appendix A, while a link to the entirety of the code can be found in Sec 4.

My code can most simply be broken down into this setup:

1. Read in WISE data
2. Read in templates
3. Define arrays holding necessary values of wavelength for templates
4. Define parameters
5. Create template
 - (a) Adjust galaxy strength relative to quasar (P)
 - (b) Redden quasar (A_V)
 - (c) Create blackbody spectrum (T)
 - (d) Adjust the redshift of the object and template (z)
 - (e) Normalize the template to match the WISE object g-band data point
6. Plot

7. User adjusts parameters, loop back to (4) and continue

The description of the subroutines can be found below:

- *WISE Data* — This section of code does everything related to reading in the WISE data. It first reads in the raw magnitude data, making a 15x8 array of that data, and a 1x15 array containing the names of each object. This also creates a 15x8 array containing the wavelengths for each band - g, r, J, Ks, W1, W2, W3, W4. There needs to be a row for each object as each object will have a different redshift, and therefore a different set of altered wavelengths. Lastly this code creates an array containing the values of W2-W3 and W1-W2, in Vega magnitudes, for each object. This will come into play with the WISE color plot, discussed above in Sec 3.2.1. [Code found in Fig. 7]
- *Galaxy Templates* — This code loads in each of the possible galaxy templates which will be used (listed above). In the interactive plot, the type of galaxy which is used in the template is a parameter which can be changed. Each of the galaxy templates, along with the original QSO template, has units of F_ν in $[\text{erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}]$, and spans 3 dex of wavelength, ranging from $0.1\mu\text{m}$ to $100\mu\text{m}$. Each dex contains 100 data points, with the whole array containing 300 data points. [Code found in Fig. 8]
- *sum* — This subroutine takes as input an array containing values of F_ν and an array containing the corresponding values of λ (in code as *lam*). From *lam*, it then determines a value of $d\lambda$ and converts that to $d\nu$, and sums the input array values of $F_\nu * d\nu$. This routine outputs a numerical value of the sum of the relative energy within the SED. [Code found in Fig. 9]
- *Galaxy Adjustment* — This code takes as input the original quasar, the original galaxy, and the parameter P . It then sets the relative strength at the rest-frame g-band λ to the value of P (i.e. $QSO[g]/GAL[g] = P$), and adjusts the rest of the galaxy template accordingly. The output of this subroutine is the adjusted galactic template. [Code found in Fig. 10]
- *Reddening* — This routine takes as input the original quasar template, the array containing the corresponding wavelengths of the template, and the amount of reddening A_V . It then applies the reddening law discussed above and outputs a template containing a reddened quasar. [Code found in Fig. 11]
- *Blackbody* — Using the *sum* subroutine, this section of code calculates the amount of flux which was absorbed by the dust reddening. It then uses the input temperature T to generate a blackbody spectrum of that same total flux spanning from $1000\mu\text{m}$ to $0.1\mu\text{m}$. [Code found in Fig. 12]
- *Normalize* — This code takes the SED template and essentially forces the values of the template and the WISE data to match on the g-band. By implementing this subroutine the template and the data will always be matched at at least one data point. [Code found in Fig. 13]
- *Flux to Magnitude* — This subroutine takes the fluxes from the template and converts them into W1, W2, or W3 Vega magnitudes. This will be important to the WISE color plot, as discussed in Sec 3.2.1. [Code found in Fig. 14]

The code listed above, when implemented, does the work of creating a custom SED template given a set of parameters. This covers one important part of the program as a whole - providing the computational and scientific backbone on which code is organized. The second part of the code is to make this computational power visual and manipulable. The aspects of these section of the code are less scientific and more administrative, which deals primarily with plotting and implementing the interactive capability. In addition, I will introduce two new parameters: a and b. These two values are simply integers that indicate the WISE object and the galaxy type, respectively.

- *Class InteractPlot* — This defines a new class of functions, called as *InteractPlot*. In this class are the main initializations of the figures on which the WISE color plot and SED will be plotted. [Code found in Fig. 15]
- *Update* — This part of the code takes the current values of the sliders and buttons, which control the parameters used to create SED, and reproduces an SED with the updated parameters, then re-plots them on the figures. The code shown in Fig. 15 is essentially the same

for four more functions, each one working slightly different. The function shown as *update* is called when any one of the sliders are changed, while the other four each correspond to a button: *next_gal*, *prev_gal*, *next_obj*, and *prev_obj*. Each of these buttons will repeat the main calculating and plotting tasks completed in *update*, but will also increment the value of either a or b by ± 1 , thereby changing the object being viewed or the galaxy template being used.

- *Main Code* — This block of code, once run, will produce the full interactive plot. This code first calls the *wise* and *gal_ad* functions to initialize the templates. It also reads in the quasar template, which contains a second row of data holding the real wavelengths corresponding to the flux values for each swire template. I then initialize the wavelength arrays for the galaxy templates (*lam*), the quasar (*QSO_lam*), and the planck function (*p_lam*). This is necessary because each of these templates work over different wavelength ranges, and thus need their own arrays. I then go through the process of extending the quasar template another two dex into the blue, in order to get the full natural effect of dust reddening. The next portion goes through the process of making the template and calculating W1, W2, and W3 magnitude values. The last section of this code defines the positions where the sliders and buttons will be placed, and connects actions (i.e. clicking or sliding) to the functions defined in the class described above. [Code found in Fig. 16]

With all these elements in place, we are then ready to begin using the code to fit SEDs.

3.2.3 Code Use

When all is said and done, the interactive plot that is produced looks something like Fig. 2:

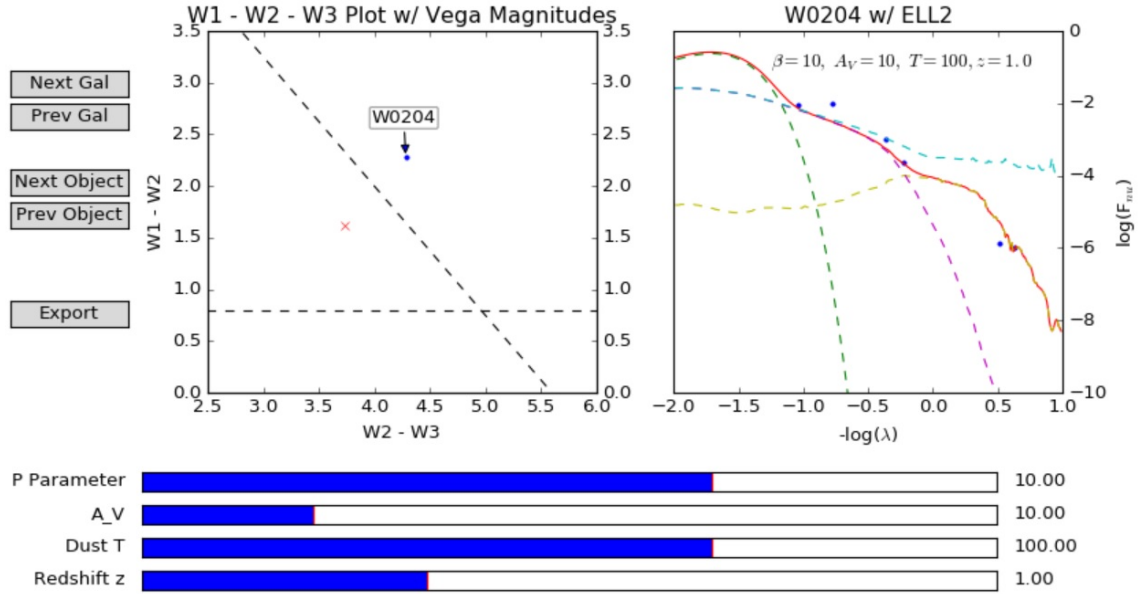


Figure 2: Interactive SED fitting plot. Left: The Vega W2-W3 v W1-W2 points for the WISE object (blue \cdot) and the template (red X). Right: $\log(F_\nu)$ v $-\log(\lambda)$ for the WISE object (blue \cdot) and the template (red solid line). The components for the template are also shown (galaxy - dashed yellow; un-reddened quasar - dashed light blue; reddened quasar - dashed purple; dust radiation - dashed green).

On the left-hand figure, there is the WISE color plot, indicating W2-W3 v W1-W2 for both the currently selected WISE object and the current template. On the right-hand plot, there is the SED template and the WISE object data points, in this case for the first object W0204. This is plotted as $\log(F_\nu)$ vs $-\log(\lambda)$. The reason that the x-axis is $-\log(\lambda)$ and not explicitly $\log(\nu)$ is because to a constant factor they are showing the same values.

$$\log(\nu) = \log\left(\frac{c}{\lambda}\right) = \log(c) + \log\left(\frac{1}{\lambda}\right) = \text{const} - \log(\lambda)$$

Plotting $-\log(\lambda)$ gives the same shape (which is what is of importance), but is easier to intuit real values of wavelength than if it were converted to frequency. Thus an x-value of 0 corresponds to $1\mu m$, an x-value of -1 corresponds to $10\mu m$, and so on.

This one plot can be used to fit each of the 15 objects in one go. Once it has begun running, the user has the ability to change:

- WISE object - a
- Galaxy type - b
- Relative strength - P
- Dust extinction - A_V
- Dust temperature - T
- Redshift - z

The four main template parameters can be changed simply by moving the sliders at the bottom of the code to the left or right, while the object and galaxy type can be changed using the buttons on the left hand side, labeled intuitively. In the code, the variable "b" is effectively the variable t in Eq. 9, indicating the type of galaxy. Once the user has decided that their object is fit well, they can hit the "Export" button on the bottom left, which will save all of the fit parameters listed above to a text file of their choosing. When the fitting is complete, this file will contain the information necessary to plot the best fits for each of the 15 objects. For simplicity/efficiency reasons, this code does not have the capacity to re-plot each best fit, however this is done simply in a separate code, linked below.

How to Intuitively Use the Fitting Code

In order to make the next user of this code maximally efficient, I will use this section to describe the intuition that I have built up on how to most quickly use the interactive portions of this program. I have found that the best way to fit the SEDs is to work outside in, or in other words to match the templates on the g, r, J, and possibly Ks points, then move on to the far WISE bands. The Ks and W1 points often lies near the point when the quasar spectrum begins to dominate over the galactic spectrum, and thus what method is used to fit these points depends on each individual field.

The first step is to fit the g, r, and J bands by choosing the proper galactic template. If there is even a small amount of reddening, the quasar portion of the template is reduced to the point that the galaxy is the dominating spectrum at these wavelengths. Therefore the choice of galaxy and redshift is all that is needed to properly match these data points. If the redshift of the object is known, this choice is much more constrained - there is only one variable: the type of galaxy. As the code is set up so that the template will always match the data on the g band data point, this leaves the user to simply cycle through the galaxy choices until they find the best match to the r- and J-band flux. In general, the slopes between the J and r data points are steeper in the elliptical galaxy templates, and gets less steep as one progresses through the spiral galaxies. It is important to note that when a galaxy does not have the J and Ks data points this is a much less accurate fit.

The next step is to fit the W3 and W4 points. These points will generally be completely dependent on the quasar template, and so one can fairly easily match these points. Assuming that there are at least a few magnitudes of dust extinction, the dust and quasar components, altered by the parameter T , and the relative strength parameter, P , will be all that is needed to match these points. When the parameter P is altered, whatever component that is *not* anchored to the g band data point will move (i.e. if the galaxy dominates at g, increasing P will move the quasar and dust components up while keeping the galaxy component steady). It is best to attempt to fit the W3 and W4 points with just the quasar template at first (i.e. keep the dust T low), and then if necessary raise the temperature of the dust so that its peak will shift far enough into the blue. Raising the temperature of the dust will move the blackbody to the right on the graph, while decreasing the temperature will move it to the left.

Last is to fit the middle, or "crossover points". These are the W2, W1, Ks, and sometimes J band data points in the middle of the plots where both the galaxy and the quasar play contributing roles. These points are the most difficult to fit to the template, as they depend on the A_V and the strength of the quasar P . As the A_V is increased, it effectively pulls the quasar template farther down in the blue. This must be fine-tuned to fit whatever slope is necessary for these interior points, in addition to some fine adjustments of P . The fitting in this section is the most finicky, and generally takes the most time to complete, however after fitting one or two objects, the intuition comes quickly.

Below, you can see pictorially how the adjustment of each slider changes the template. In each case, the arrows indicate what is changed when the slider values are increased, and these representations should aid in building an intuition of how to effectively use the program.

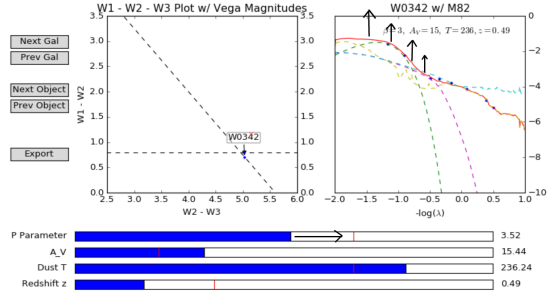


Figure 3: A depiction of what happens to the template when P is increased. Moving P only affects the component of the template which is *not* dominant at the g-band.

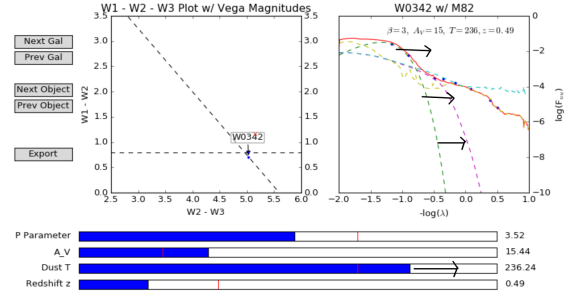


Figure 5: A depiction of what happens when one increases T . Note that this only affects how the planck function from the dust moves, nothing else.

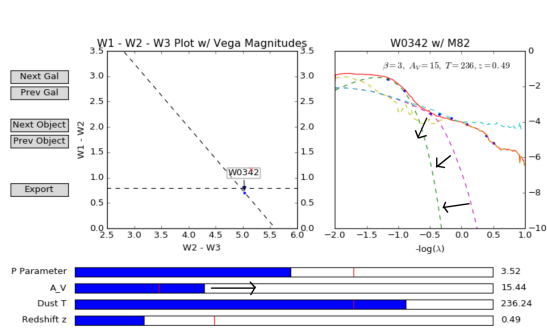


Figure 4: A depiction of what happens to the quasar template as A_V is increased. The more A_V , the further into the red the template gets depressed.

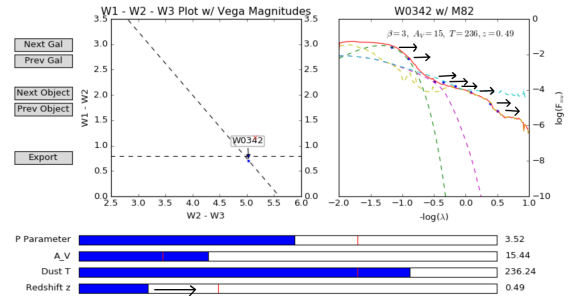


Figure 6: A depiction of what happens when z is adjusted. This variable moves the *data points* from side to side, and thus the template shifts up and down depending on its shape near the g-band.

As one might expect, doing these steps in order every time will usually not give the best possible fit on the first try. There will always be some tinkering that has to be done with the parameters to fit the objects just right. In some cases it will turn out that there is little more to do and the fit is fantastic, while in other instances the user will have to keep fine-tuning the parameters a good bit to find the best fit.

Once an initial fit is found for each object and the parameters are exported to a text file, we are in the position to be able to fine-tune each one. An extension which will be added on to this code is that when each object viewed, the best fit parameters will be the default on the plot, as opposed to the more arbitrary values which are there now.

3.3 Results

After performing a first round of SED fitting using the interactive plot, I was able to get a decent initial fit for the majority of the objects (12 / 15). The parameters corresponding to the best fits are shown below in Tab. 3, while each best fit plot can be found in Appendix B.

Object	P	A_V	T	z	a	b
W0204	68.37	15.44	6.84	1.49	0	4
W0342	2.76	8.07	231.06	[0.47]	1	8
W0404	46.93	5.18	329.29	1.43	2	0
W0612	12.02	16.80	72.26	1.16	3	0
W0739	10.41	16.80	258.11	1.04	4	7
W0943	9.53	6.86	459.00	1.70	5	7
W1046	12.99	31.22	107.65	0.66	6	7
W1210	46.93	12.95	252.46	1.03	7	6
W1238	13.43	0.77	518.43	[2.25]	8	7
W1332	34.42	13.19	55.40	1.50	9	3
W1521	63.98	10.55	367.84	0.51	10	3
W1703	41.09	14.88	57.27	[1.08]	11	7
W1958	91.18	9.11	57.27	[1.80]	12	6
W2331	31.50	4.78	376.07	1.40	13	0
W2345	55.4	7.5	202.32	1.98	14	7

Table 3: Parameters corresponding to the best fit for each object. The z values in brackets are known, while all other z values are free parameters.

For temperatures which are lower than $\sim 90K$, the blackbody spectrum does affect the template near any of the data points, and so the temperature cannot be thought of as a matched parameter. We can infer that the dust is cool, but cannot estimate the actual temperature. One of the pieces of information that we hoped to learn from this is to determine at what wavelengths the quasar light begins to dominate over the galaxy. In most cases, this happened somewhere in the range of the Ks to W1 bands, $[2.163\mu m] - [3.4\mu m]$, although there are a few exceptions to this. At the bluer wavelengths (g, r, J), the galaxy dominated the templates, while the redder wavelengths (W2, W3, W4) are typically dominated by the quasar.

Another interesting piece of information that was gleaned from these fits is that in many of the objects, the only way our model was able to properly fit the observed data was with temperatures in the range of roughly $200K - 500K$. This differs with the current literature on dust temperature in similar (but not necessarily the same) objects, Hot Dust Obscured Galaxies (Hot DOGs), where the temperature is expected to be in the range $60K - 100K$. In order to test the feasibility of these high dust temperatures, we used an order of magnitude estimate to see if the temperatures yield a viable radius R_{dust} for a hypothetical shell of dust providing the extinction and re-radiation around a quasar.

We start with the relation

$$\frac{L_*}{(4\pi d^2)} \pi a^2 Q_{abs} \approx 4\pi a^2 \sigma T_d^4 Q_{em} \quad (11)$$

where Q_{abs} is the absorption efficiency, Q_{em} the emission coefficient, a the radius of the dust grains, and d the distance of the dust from the quasar (treated as a point source). We can then solve for the dust distance in parsecs as

$$d_{pc} \approx \left(\frac{0.62}{T_d}\right)^2 \left(\frac{L_*}{L_\odot}\right)^{\frac{1}{2}} \left(\frac{Q_{abs}}{Q_{em}}\right)^{\frac{1}{2}} \quad (12)$$

For a blackbody emitter, the ratio of Q_{em} to Q_{abs} is roughly 1:1. However dust grains are not perfect blackbodies when absorbing and emitting in the infrared - the size of the dust is much lower than the wavelength of the light, which makes them poor emitters. For dust in the infrared, the value of $(Q_{abs}/Q_{em})^{\frac{1}{4}} \sim 3 - 7$. Therefore the value of $(Q_{abs}/Q_{em})^{\frac{1}{2}}$ in Eq. 12 is $\sim 10 - 50$. By choosing an estimated luminosity of a quasar as $L \approx 10^{12} L_\odot$, a temperature of 300K, and using the limits of the Q term, this yields an estimated dust distance of $\sim 8pc - 38pc$. One other popular

model for dust around quasars is a torus model, which has an estimated inner and outer radius of $\sim 1pc$ and $\sim 100pc$, respectively. Our numbers are well within this range, and thus we can conclude that our model is not inconsistent with others currently being used. What is of interest then is to investigate and see whether our objects are in fact different from the studied Hot DOGs. By the selection process, the SEDs have similar slopes across the W1-W3 bands, but it is not known whether or not our W4 points are different from that of Hot DOGs. This is an interesting question which will be explored further as the project progresses and more data is gathered on our sample.

The dust component of this model is at this point inconclusive. Many fitting methods consider torus dust models, dust at multiple temperatures, and other such features, however each model is just that - a model. It is possible that there is both a hot *and* cold dust component to these objects, but the range of our data does not allow for extrapolation into the wavelengths where a cold dust would become important. In the future, there will be new data from ALMA, which will give constraints for our objects further into the IR spectrum, as well as radio data points.

4 Conclusion

Over the course of the semester I was able to make significant progress in moving this project forward while further developing my coding repertoire. In addition to obtaining the magnitudes from fits images of the objects, I put this data through its first round of analysis, both confirming our hypothesis of what the objects are and gaining insight into the rough physical nature of the systems.

From the fitted templates, we gained useful information about possible quasar strengths, dust temperatures, and by extension the size of the absorbing dust cloud. These fits have also given possible first estimates of the redshifts of the galaxies, as well as potential constraints on their galactic types. Lastly, these fits confirmed the predicted model of the objects as being heavily dust-obscured active galactic nuclei.

While there has been a significant amount of work done to obtain the fits for these SEDs, they are merely a starting point. Moving this project forward, there must be more advanced fits done, such as to minimize a χ^2 value and find the statistical best fit values for each parameter. An extension of this code would be to apply the by-hand fits into an optimization routine, finding the statistical best fits for each model. There are also certain fields which are missing data in the J and Ks bands, leaving a large section in the middle of each afflicted SED unconstrained. There are currently efforts being made to obtain this data by Prof. Whittle, and it will be necessary to get a more complete idea of the makeup of the objects. Additionally, images obtaining spectra for each of these objects are being observed, which will allow for the accurate determination of the redshifts. This will be another constraint on each of the SED models. Lastly, there will be an effort to create an RGB image for each field, to further the first science goal of characterizing the environment of the galaxies. The first step of fitting each SED to a template can give insight into each of the galactic environments, and is a positive step forward in the overall goals of the project.

External Links

The necessary code, text files, and write-ups can be found in the GitHub repository `pme5vc/Senior-Thesis-May2018`, or found by following the link:

<https://github.com/pme5vc/Senior-Thesis-May2018>

Notes

¹The Two Micron All Sky Survey (2MASS) M.F. Skrutskie, R.M. Cutri, R. Stiening, M.D. Weinberg, S. Schneider, J.M. Carpenter, C. Beichman, R. Capps, T. Chester, J. Elias, J. Huchra, J. Liebert, C. Lonsdale, D.G. Monet, S. Price, P. Seitzer, T. Jarrett, J.D. Kirkpatrick, J. Gizis, E. Howard, T. Evans, J. Fowler, L. Fullmer, R. Hurt, R. Light, E.L. Kopan, K.A. Marsh, H.L. McCallon, R. Tam, S. Van Dyk, and S. Wheelock, 2006, AJ, 131, 1163. (Bibliographic Code: 2006AJ....131.1163S)

²Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and

resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss.org.

SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University.

³This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

⁴This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

⁵Wright et al. 2010, *AJ*, 140, 1868

⁶Calzetti, D., Armus, L., Bohlin, R.C. et al. 2000, *ApJ*, 533, 682

⁷Polletta et al. 2007, *ApJ*, 663, 81

Appendix

A Code

```
def wise():  
    #Reads in the WISE data  
    # Reads in the AB magnitudes, errors, and flux range in um for each object  
    magAB = np.loadtxt('AB_mags.txt')  
    errors = np.loadtxt('AB_errors.txt')  
    with open('objects.txt') as f:  
        objects = f.readlines()  
        objects = [line.rstrip('\n') for line in open('objects.txt')]  
  
    wise_flux = np.zeros((15,8))  
    wise_fluxerr = np.zeros((15,8))  
  
    for i in range(15):  
        for j in range(8):  
            if errors[i,j] == 9.999:  
                errors[i,j] = 0.000  
            if magAB[i,j] == 0.:  
                continue  
            wise_flux[i,j] = 10**(-0.4*(magAB[i,j] - 8.926))  
            wise_fluxerr[i,j] = 10**(-0.4*(magAB[i,j] + errors[i,j] - 8.926))  
  
    wise_error = wise_fluxerr - wise_flux  
  
    #Array containing the wavelengths for each WISE object in each band: (g r J Ks W1 W2 W3 W4)  
    wise_lam = np.zeros((15,8))  
  
    for i in range(15):  
        wise_lam[i] = (0.474, 0.620, 1.247, 2.163, 3.4, 4.6, 12., 22.)  
  
    #WISE values of row1: W2 - W3, and row2: W1 - W2  
    wise_w123 = np.zeros((2,15))  
    for i in range(15):  
        #The magnitudes are converted back into Vega mags, which were the magnitudes used by Lonsdale et. al.  
        wise_w123[0,i] = (magAB[i,5] - 3.339) - (magAB[i,6] - 5.174)  
        wise_w123[1,i] = (magAB[i,4] - 2.699) - (magAB[i,5] - 3.339)  
  
    return wise_flux, wise_lam, wise_error, wise_w123, objects
```

Figure 7: Function that reads in the data of the WISE objects, such as the flux, the wavelengths, errors, and names of the objects.

```
def load_gal():  
    galaxy = np.zeros((10,300))  
    names = ['ELL2', 'ELL5', 'ELL13', 'S0', 'Sa', 'Sb', 'Sc', 'Sd', 'M82', 'ARP220']  
  
    ELL2_orig = np.loadtxt('templates_recast/ELL2.txt')  
    ELL5_orig = np.loadtxt('templates_recast/ELL5.txt')  
    ELL13_orig = np.loadtxt('templates_recast/ELL13.txt')  
    S0_orig = np.loadtxt('templates_recast/S0.txt')  
    Sa_orig = np.loadtxt('templates_recast/Sa.txt')  
    Sb_orig = np.loadtxt('templates_recast/Sb.txt')  
    Sc_orig = np.loadtxt('templates_recast/Sc.txt')  
    Sd_orig = np.loadtxt('templates_recast/Sd.txt')  
    M82_orig = np.loadtxt('templates_recast/M82.txt')  
    ARP220_orig = np.loadtxt('templates_recast/ARP220.txt')  
  
    galaxy[0] = ELL2_orig[0]  
    galaxy[1] = ELL5_orig[0]  
    galaxy[2] = ELL13_orig[0]  
    galaxy[3] = S0_orig[0]  
    galaxy[4] = Sa_orig[0]  
    galaxy[5] = Sb_orig[0]  
    galaxy[6] = Sc_orig[0]  
    galaxy[7] = Sd_orig[0]  
    galaxy[8] = M82_orig[0]  
    galaxy[9] = ARP220_orig[0]  
  
    return galaxy, names
```

Figure 8: Reads in the galactic SED templates.

```
def sum(array, lam): #Sums the values in a template: (SUM(F_nu * dnu))
    a = len(array)
    tot = 0.

    for i in range(a-1):
        dlam = abs(lam[i+1] - lam[i])
        dnu = cu / lam[i]**2 * dlam

        tot += array[i] * dnu

    return tot
```

Figure 9: Sums the fluxes in an array.

```
def gal_ad(gal_orig, qso_orig, p):
    gal = np.zeros(len(gal_orig))

    gal[237] = qso_orig[237] / p
    x = gal[237] / gal_orig[237]
    for j in range(len(gal_orig)):
        gal[j] = gal_orig[j] * x

    return gal
```

Figure 10: Code to adjust the relative strength of the galaxy and quasar templates at the g band.

```
def reddening(qso_orig, lam, A_V):
    R_V = 4.05

    A_lam = np.zeros(len(lam)) #Actually calculating A_lam / A_V

    const = (2.659/R_V * (-1.857 + 1.04/2.2) + 1.0) * 2.2**1.8
    const1 = (2.659/R_V * (-2.156 + 1.509/0.1 - 0.198/(0.1**2) + 0.011/(0.1**3)) + 1.0) * 0.1**1.8

    for i in range(len(lam)):
        if lam[i] >= 0.12:
            if lam[i] < 0.63:
                A_lam[i] = 2.659/R_V * (-2.156 + 1.509/lam[i] - 0.198/(lam[i]**2) + 0.011/(lam[i]**3)) + 1.0
            if lam[i] >= 0.63:
                if lam[i] <= 2.20:
                    A_lam[i] = 2.659/R_V * (-1.857 + 1.04/lam[i]) + 1.0
                elif lam[i] > 2.20:
                    A_lam[i] = const * lam[i]**-1.8
            if lam[i] < 0.12:
                A_lam[i] = const1 * lam[i]**-1.8

    QSO_red = np.zeros(len(qso_orig))

    for i in range(len(qso_orig)):
        QSO_red[i] = qso_orig[i] * 10**(-0.4 * A_V * A_lam[i])

    return QSO_red
```

Figure 11: Applies a reddening law to quasar template.

```
def planck(lam, p_lam, qso_orig, qso_red, T):
    planck = p_lam**(-3) / (np.exp(14400. / p_lam / T)-1) #Planck function

    dust_abs = sum(qso_orig, lam) - sum(qso_red, lam)
    planck_func = np.zeros(len(p_lam))

    alpha = dust_abs / sum(planck, p_lam)
    planck_func = planck * alpha

    return planck_func
```

Figure 12: Using the sum subroutine, creates a blackbody spectrum with the same sum flux as was taken from the quasar template during reddening.

```

def norm(template, lam, wise_flux, wise_lam): #normalizes to template to the g-band point of the WISE data
    c = 0.
    tot = 0.
    temp = np.zeros(len(template))

    for k in range(len(template)): #making a new, cloned template, because without doing this it update the input
        temp[k] = template[k] #template, and I don't want that

    for j in range(len(lam)):
        if lam[j] >= wise_lam - 0.02:
            if lam[j] <= wise_lam + 0.02:
                c += 1.
                tot += temp[j]
    avg = tot / c

    x = avg / wise_flux
    temp /= x

    return temp

```

Figure 13: Normalizes the template to be mapped on the g band WISE data point.

```

def f2mag(val, num): #Converts the W1, W2, and W3 fluxes in the template to Vega magnitudes
    if num == 1.:
        mag = -2.5 * np.log10(1e23 * val) + 8.962 - 2.699
    elif num == 2.:
        mag = -2.5 * np.log10(1e23 * val) + 8.962 - 3.339
    elif num == 3.:
        mag = -2.5 * np.log10(1e23 * val) + 8.962 - 5.174

    return mag

```

Figure 14: Converts fluxes from the template into the W1, W2, and W3 Vega magnitudes.

```

class InteractPlot:
    def __init__(self):
        #Defines the first figure which holds the W2-W3 v W1-W2 points and graph
        self.fig1 = plt.figure(figsize=(12,6))
        plt.clf()
        self.ax1 = self.fig1.add_subplot(121)
        plt.subplots_adjust(left=0.25, bottom=0.35)
        plt.axis([2.5,6,0.0,3.5])

        x = np.arange(-1,10,.1)
        plt.plot(x, x/x*0.8, 'k--')
        plt.plot(x, -1.25*x + 7, 'k--')

        plt.xlabel('W2 - W3')
        plt.ylabel('W1 - W2')
        plt.title('W1 - W2 - W3 Plot w/ Vega Magnitudes')

        #Defines the figures which will plot the SED on top of each set of WISE points
        self.ax2 = self.fig1.add_subplot(122)

    def plot(self, xdata, ydata, ptype):
        self.ax1.plot(xdata, ydata, ptype)

    a = 0          #defines which object will be plotted with the SED (0 <= i <= 14)
    b = 0          #defines which galaxy type will be the first one plotted

    def update(self, val):
        p = 10**(sp.val)          #retrieves current values from sliders and re-calculates the templates
        sp.valtext.set_text("%.2f" % p)
        av = sav.val
        t = 10**(st.val)
        st.valtext.set_text("%.2f" % t)
        z = sz.val

        self.a %= 15
        self.b %= 10

        wise_lam_new = wise_lam[self.a] / (z + 1)

        gal = gal_ad(galaxy[self.b], QSO_orig[0], p)
        QSO_red = reddening(QSO_new, QSO_lam, av)
        p_func = planck(QSO_lam, p_lam, QSO_new, QSO_red, t)

        template = gal

        for j in range(len(gal)):
            template[j] += p_func[j+100]
            template[j] += QSO_red[j]

        zshift = int(100*np.log10(z + 1))
        W1 = f2mag(template[147 + zshift], 1)
        W2 = f2mag(template[134 + zshift], 2)
        W3 = f2mag(template[92 + zshift], 3)

        l.set_xdata(W2-W3)
        l.set_ydata(W1-W2)

        temp = norm(template, lam, wise_flux[self.a,0], wise_lam_new[0])          #normalizes the template to the g-band
        n_factor = np.log10(temp[1]) - np.log10(template[1])

        self.ax2.cla()
        self.ax2.plot(-np.log10(wise_lam_new), np.log10(wise_flux[self.a]), 'b.', label=objects[self.a])
        self.ax2.set_title(objects[self.a] + ' w/ ' + gal_names[self.b])
        self.ax2.set_xlabel('-log($\lambda$)')
        self.ax2.yaxis.set_label_position("right")
        self.ax2.yaxis.tick_right()
        self.ax2.set_ylabel('log(F$_{nu}$)')
        self.ax2.axis([-2,1,-10,-0])
        self.ax2.plot(negloglam, np.log10(temp), 'r-')
        self.ax2.plot(p_negloglam, np.log10(p_func) + n_factor, 'g--')
        self.ax2.plot(negloglam, np.log10(gal) + n_factor, 'y--')
        self.ax2.plot(QSO_negloglam, np.log10(QSO_red) + n_factor, 'm--')
        self.ax2.plot(negloglam, np.log10(QSO_orig[0]) + n_factor, 'c--')
        self.ax2.text(-1.25, -1, r'$\beta$=' + str(int(p)) + ', A_V=' + str(int(av)) + ', T=' +
            str(int(t)) + ', z=' + str(round(z,2)) + '$')
        self.ax2.draw()

```

Figure 15: Defines the initialization of the Class *InteractPlot*. Initializes the figures to be plotted, and shows one example of the segments of code which updates the plots. In this case, this section of code (*def update():*) changes the SED template based on the movement of one of the four sliders for each of the parameters.

```
#####Initializations#####
#Loads WISE data
wise_flux, wise_lam, wise_error, wise_w123, objects = wise()

#The data from these templates is in two rows, the first row containing the flux, the second row containing the wavelength
#The flux is in units of [erg cm-2 s-1 Hz-1], while the wavelength is in [um]
QSO_orig = np.loadtxt('templates_recast/QSO1.txt')

galaxy, gal_names = load_gal()

lam = QSO_orig[1]                                #array of wavelengths
negloglam = -np.log10(lam)                        #array of -Log(wavelength), [-2,1]
QSO_negloglam = np.arange(-2,3,0.01)             #array of new -Log(wavelength) for QSO [-2,3]
QSO_lam = 10**(-QSO_negloglam)                   #new QSO Lambda
p_negloglam = np.arange(-3,1,0.01)               #array of -Log(wavelength) for planck function, [-3,1]
p_lam = 10**(-p_negloglam)                       #array of wavelengths for planck function

QSO_new = np.zeros(len(QSO_negloglam))

for i in range(len(QSO_negloglam)):               #expands Quasar another 2 dex, setting it as const in nu*F_nu
    if i <= 299:
        QSO_new[i] = QSO_orig[0][i]
    else:
        QSO_new[i] = QSO_orig[0][299] * QSO_lam[i] / QSO_lam[299]

#initializes the plots
myplot = InteractPlot()

#initial values of the sliders and template (p0 and T0 are Log values)
p0 = 1.
A_V0 = 10.
T0 = 2.
z0 = 1.

a0 = 0
b0 = 0

wise_lam_new = wise_lam[a0] / (z0 + 1)           #applies z-shift law to the WISE points

gal = gal_ad(galaxy[b0], QSO_orig[0], 10**(p0))
QSO_red = reddening(QSO_new, QSO_lam, A_V0)
p_func = planck(QSO_lam, p_lam, QSO_new, QSO_red, 10**(T0))

template = gal

for j in range(len(gal)):
    template[j] += p_func[j+100]
    template[j] += QSO_red[j]

#Points corresponding to the wavelength bands are g-237 r-220 J-190 Ks-166 W1-147 W2-134 W3-92 W4-66
zshift = int(100*np.log10(z0 + 1))
W1 = f2mag(template[147 + zshift], 1)
W2 = f2mag(template[134 + zshift], 2)
W3 = f2mag(template[92 + zshift], 3)

#plots the WISE points on the first figure
myplot.plot(wise_w123[0,a0], wise_w123[1,a0], 'b.')
plt.subplot(121)
plt.annotate(
    objects[a0],
    xy=(wise_w123[0,a0], wise_w123[1,a0]), xytext=(20, 20),
    textcoords='offset points', ha='right', va='bottom',
    bbox=dict(boxstyle='round,pad=0.1', fc='white', alpha=0.4),
    arrowprops=dict(arrowstyle = '-|>', connectionstyle='arc3,rad=0'))
```

```

ax_1 = myplot.ax1.twinx()
plt.axis([2.5,6,0.0,3.5])
l, = plt.plot(W2-W3, W1-W2, 'rx') #defines the point which will be slid on the color plot
axp = plt.axes([0.2, 0.20, 0.65, 0.03]) #defines the position of the sliders
axav = plt.axes([0.2, 0.15, 0.65, 0.03])
axt = plt.axes([0.2, 0.1, 0.65, 0.03])
axz = plt.axes([0.2, 0.05, 0.65, 0.03])

axnextgal = plt.axes([0.1, 0.80, 0.09, 0.04])
axprevgal = plt.axes([0.1, 0.75, 0.09, 0.04])
axnextobj = plt.axes([0.1, 0.65, 0.09, 0.04])
axprevobj = plt.axes([0.1, 0.60, 0.09, 0.04])

axexport = plt.axes([0.1, 0.45, 0.09, 0.04])

#initializes the sliders
sp = Slider(axp, 'P Parameter', -1, 2, valinit=p0)
sav = Slider(axav, 'A_V', 0, 50, valinit=A_V0)
st = Slider(axt, 'Dust T', 0, 3, valinit=T0)
sz = Slider(axz, 'Redshift z', 0, 3, valinit=z0)

bnextgal = Button(axnextgal, 'Next Gal')
bprevgal = Button(axprevgal, 'Prev Gal')
bnextobj = Button(axnextobj, 'Next Object')
bprevobj = Button(axprevobj, 'Prev Object')
bexport = Button(axexport, 'Export')

sp.on_changed(myplot.update)
sav.on_changed(myplot.update)
st.on_changed(myplot.update)
sz.on_changed(myplot.update)

bnextgal.on_clicked(myplot.next_gal)
bprevgal.on_clicked(myplot.prev_gal)
bnextobj.on_clicked(myplot.next_obj)
bprevobj.on_clicked(myplot.prev_obj)
bexport.on_clicked(myplot.export)

plt.subplot(122)
plt.plot(-np.log10(wise_lam_new), np.log10(wise_flux[a0]), 'b.', label=objects[a0])
plt.title(objects[a0] + ' w/ ' + gal_names[b0])
plt.axis([-2,1,-10,-0])

plt.show()

```

Figure 16: The main portion of the code. Running this section will start the interactive plot.

B Fitted SEDs

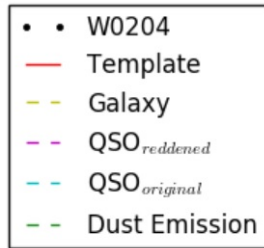


Figure 17: Legend for the best fit SED plots.

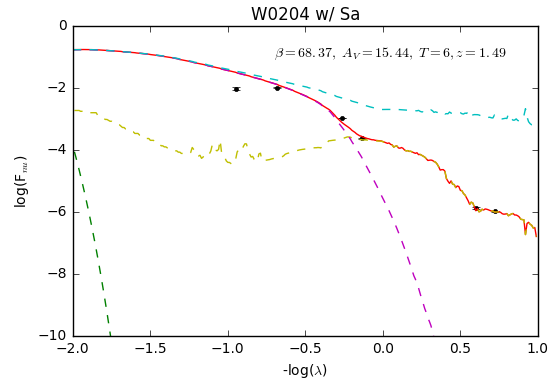


Figure 18: Best fit for object W0204

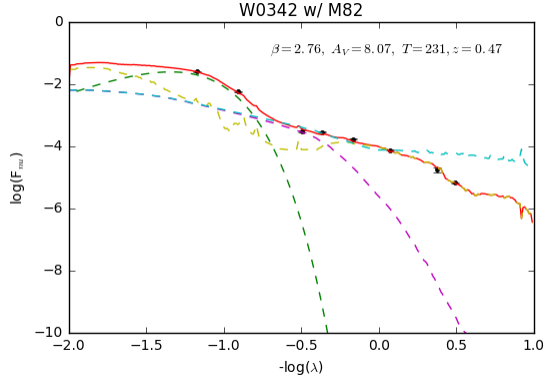


Figure 19: Best fit for object W0342

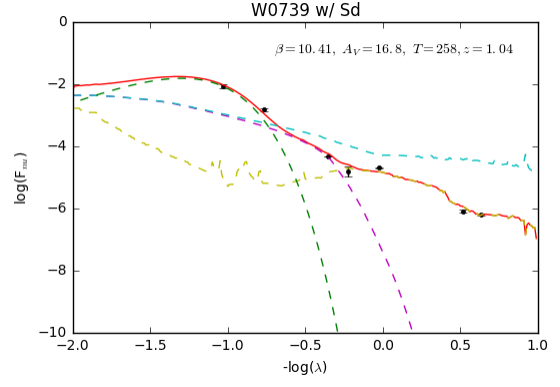


Figure 22: Best fit for object W0739

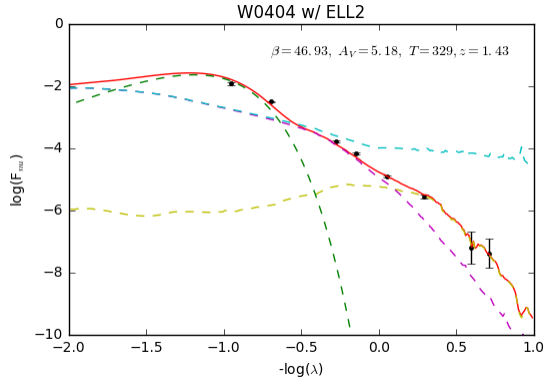


Figure 20: Best fit for object W0404

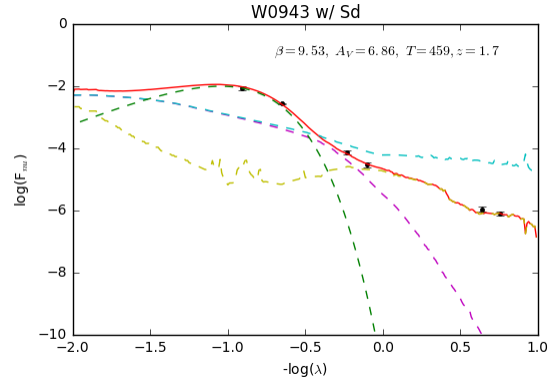


Figure 23: Best fit for object W0943

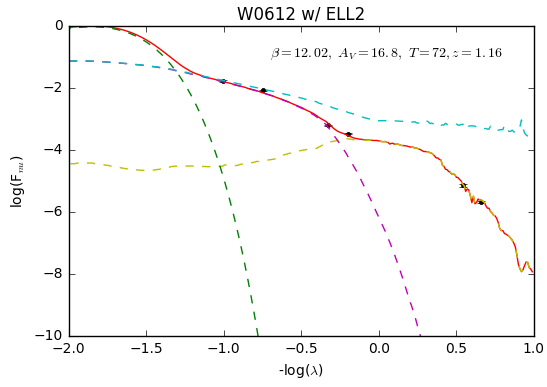


Figure 21: Best fit for object W0612

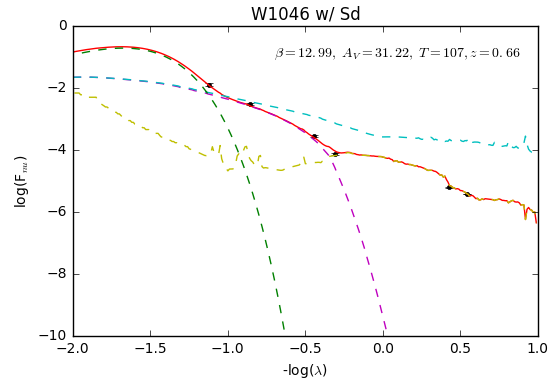


Figure 24: Best fit for object W1046

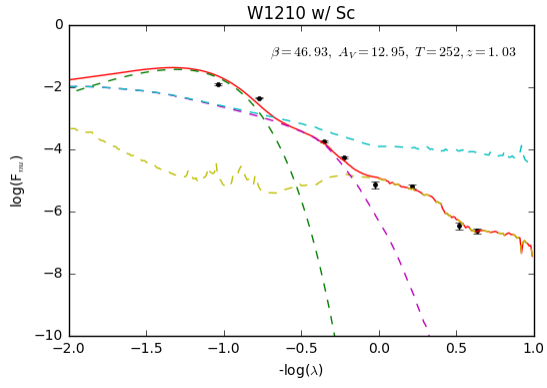


Figure 25: Best for for object W1210

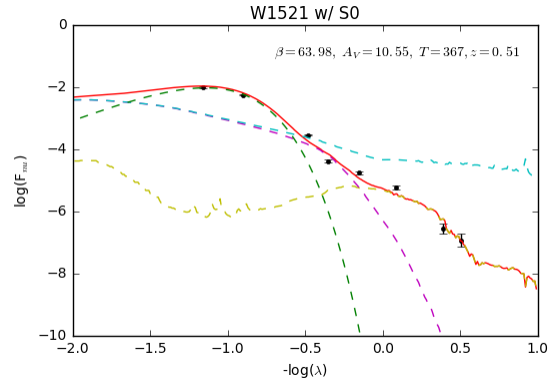


Figure 28: Best for for object W1521

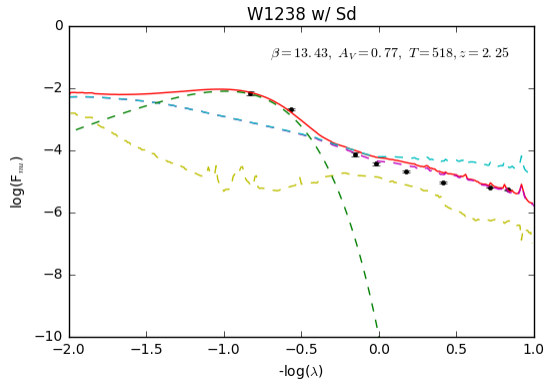


Figure 26: Best for for object W1238

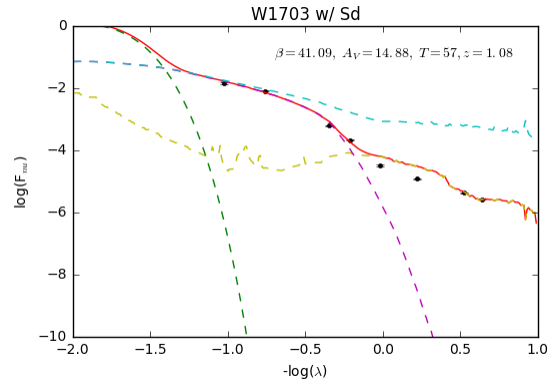


Figure 29: Best for for object W1703

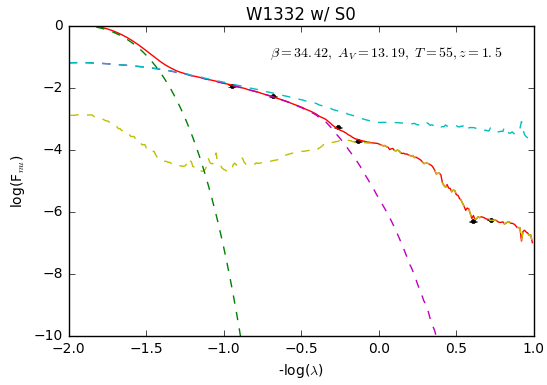


Figure 27: Best for for object W1332

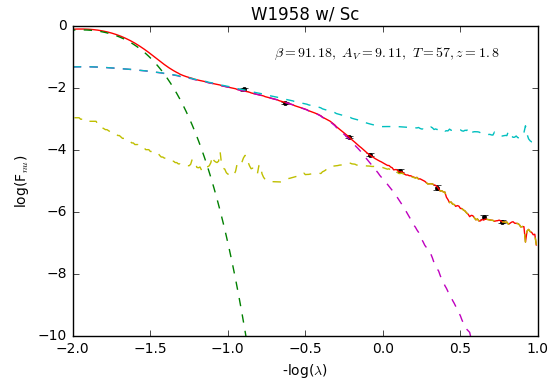


Figure 30: Best for for object W1958

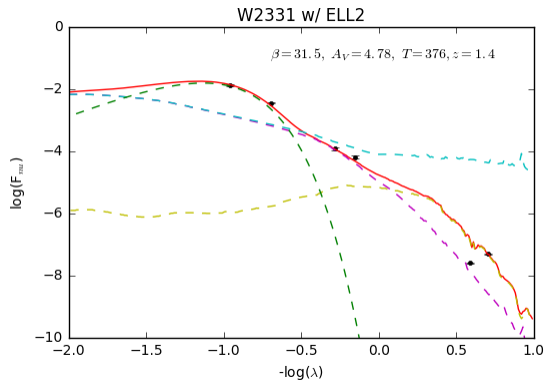


Figure 31: Best for for object W2331

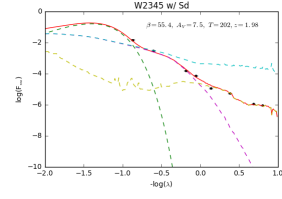


Figure 32: Best for for object W2345